Top quark physics at lepton colliders

loosely based on presentations at the 2015 LC top workshop

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Behind Precision Workshop, CERN, february 2016

Acknowledging input/contributions from:

F. Bach (DESY), W. Bernreuther (RWTH Aachen), A. Hoang (U. Vienna), P. Marquard, P. Ruiz-Femenia (MPI), M. Stahlhofen (DESY)
F. Richard, F. le Diberder, R. Poeschl (LAL Orsay)M. Boronat, J. Fuster, I. Garcia, M. Perelló, E. Ros (IFIC Valencia)

Top quark physics

One of (at least) two SM particles to escape (direct) scrutiny at lepton colliders

It is **important** to know its properties: contributions through loops

- Top mass, width

It is a quark we **can** characterize well: top-anti-top tagging, polarization

- Production asymmetries

If top is part of the hierarchy problem, is the top sector part of the solution too?

- Top quark Yukawa coupling

Is top connected to new physics?

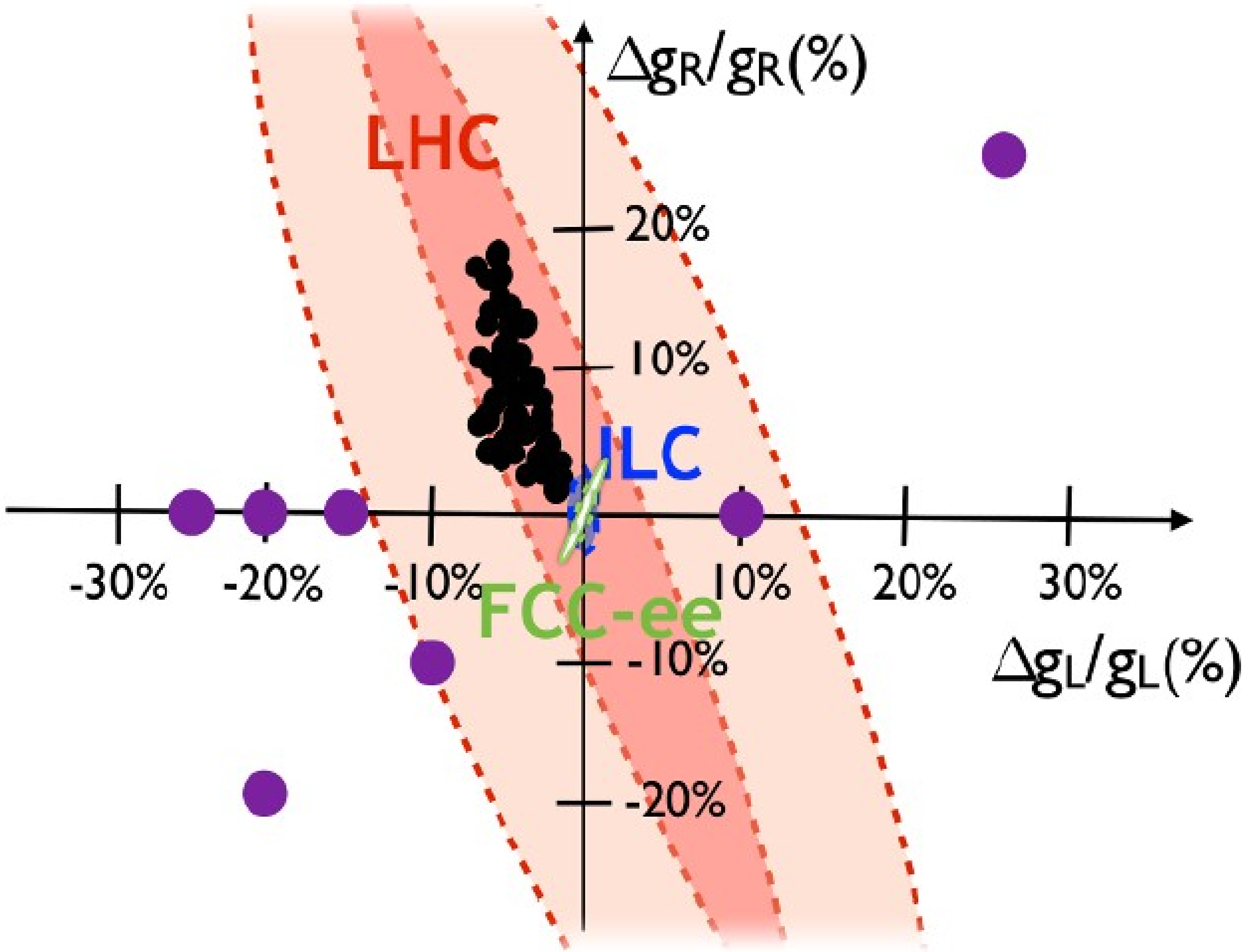
- FCNC decays

BSM physics

Certain classes of SM extensions predict sizable deviations from the SM prediction for the $t\bar{t}Z$ coupling

Extra dimension models typically yield order 10% deviations for Λ ~ 1 TeV

See: Stefania de Curtis, this workshop



● 5D models proposed by several authors
Richard, arXiv:1403.2893

● 4D Composite Higgs Model
Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

The SM precision measurement IS the search for new physics

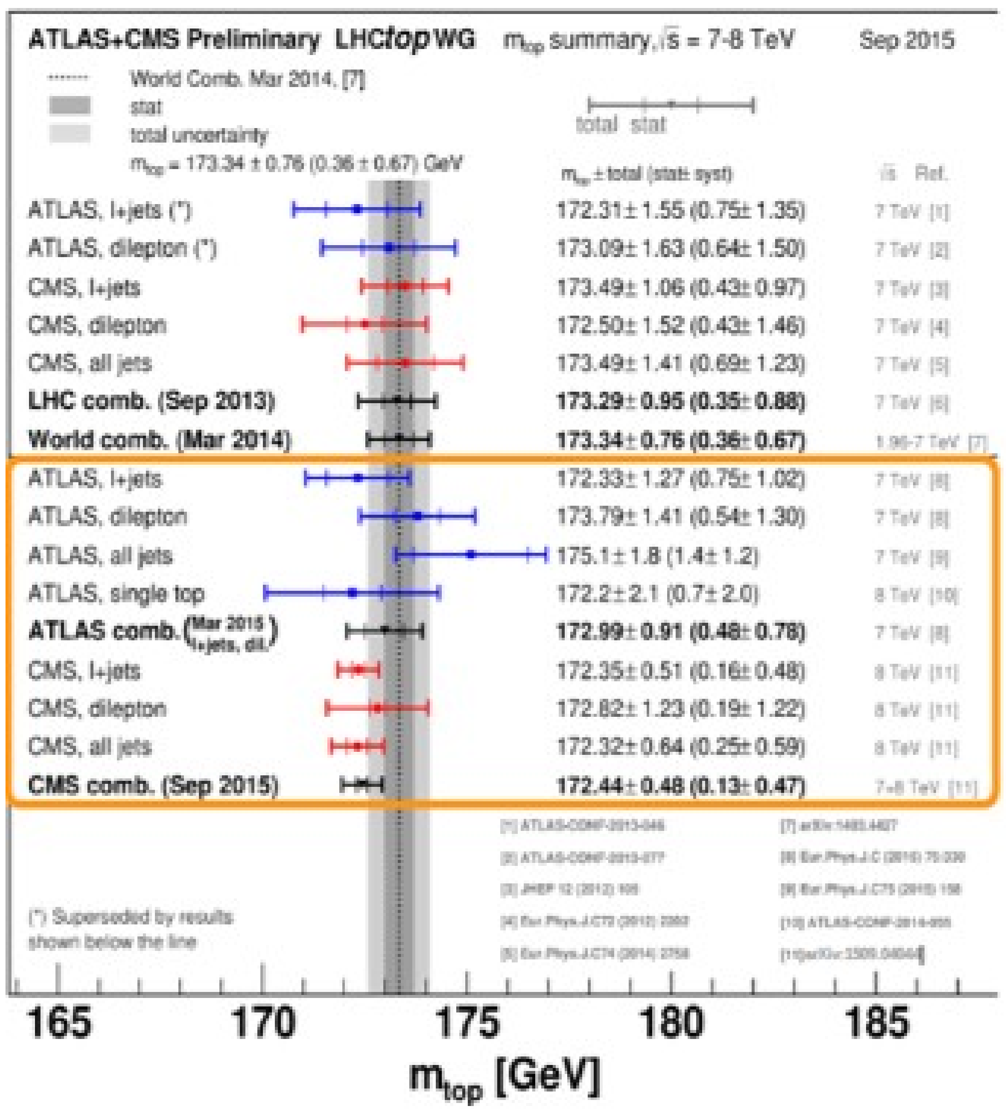
Current status: Top Mass

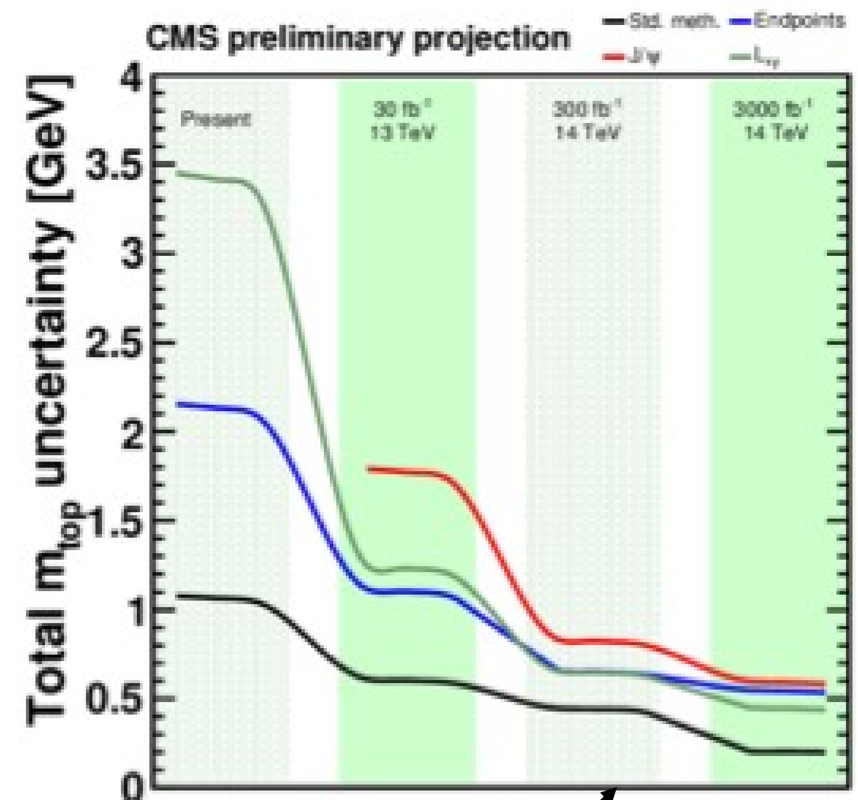
Hadron colliders (LHC and Tevatron) achieved a precision in the measurement of the top mass of **~ 0.76 GeV in March 2014**

arXiv:1403.4427

Combination of consistent set of measurements from 4 experiments (ATLAS, CMS, CDF and D0)

New results from CMS even more precise
~ 0.5 GeV September 2015



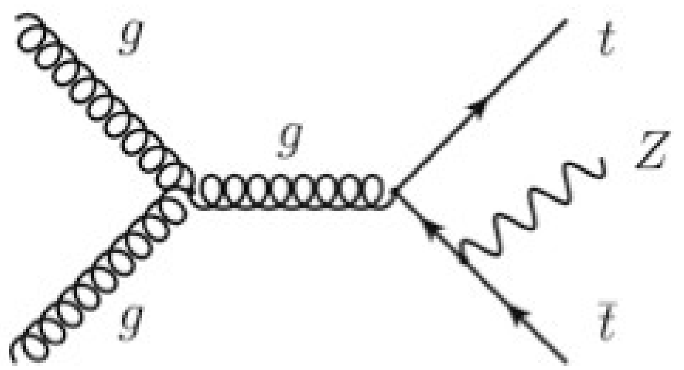


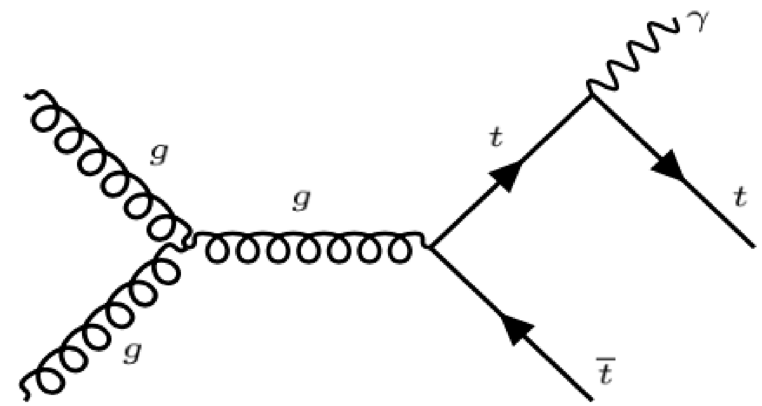
LHC already **exceeding prospects**

CMS expects 200 MeV after 3000 fb^{-1} (conventional method, *CMS-FTR-13-017-PAS)* based on "*assumptions [that] are optimistic but not unrealistic*"

Issues with interpretation not accounted for.
A showstopper? See: Gennaro Corcella

Current status: EW couplings





Complex, multi-channel analysis.

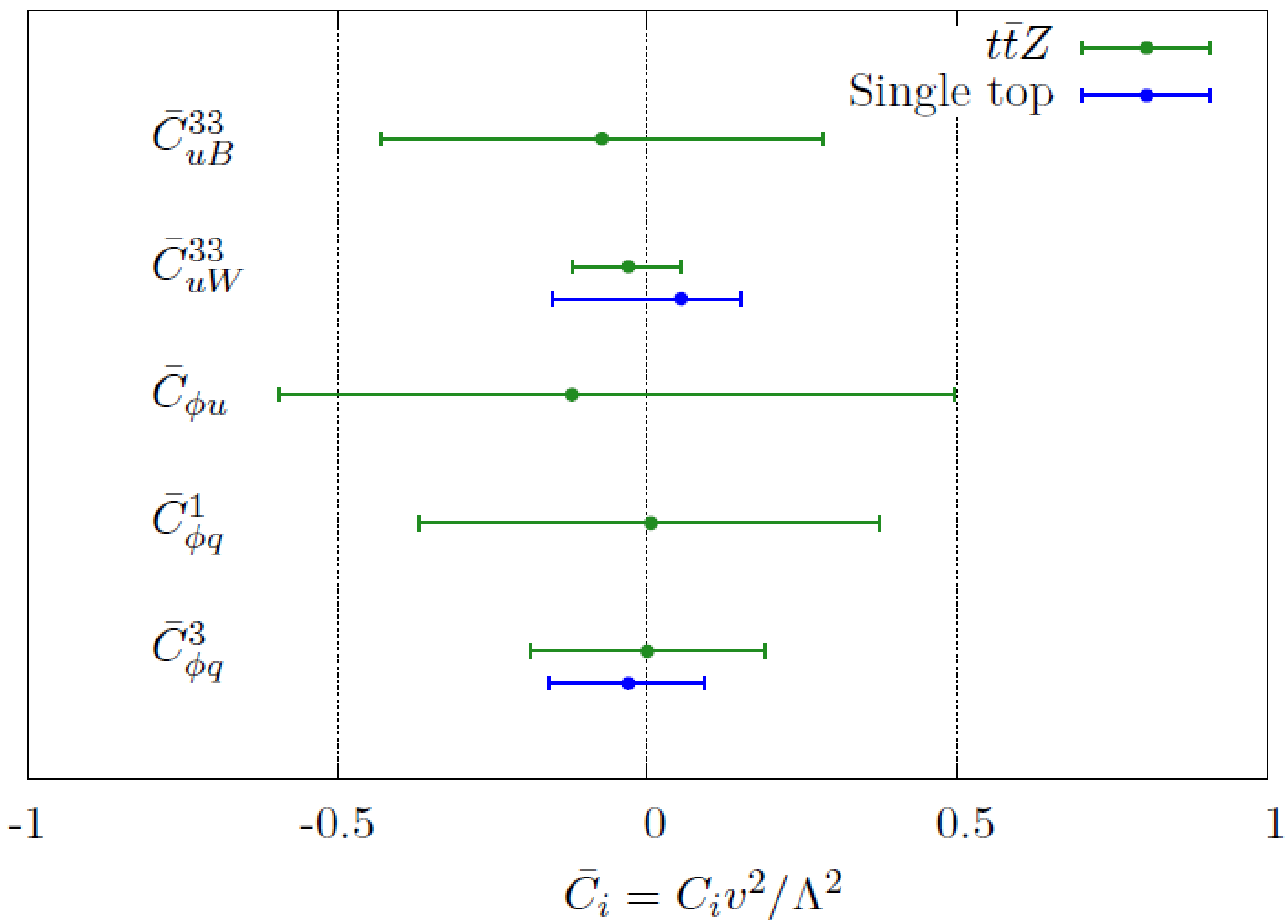
5 σ observation for all top + EW associated production channels!!

	ttW	ttZ	ttγ
ATLAS	5.0 σ ArXiv:1509.05276	4.2 σ ArXiv:1509.05276	5.3 σ (7 TeV) ArXiv:1502.00586
CMS	4.8 σ ArXiv:1510.01131	6.4 σ ArXiv:1510.01131	CMS-PAS-TOP-13-011

LHC prospects

Data from Tevatron and LHC (from cross-sections to spin correlations) provide precise multi-dimensional constraint

Simultaneous fit to effective operators affecting top quark sector:
ArXiv:1506.08845
ArXiv:1512.03360

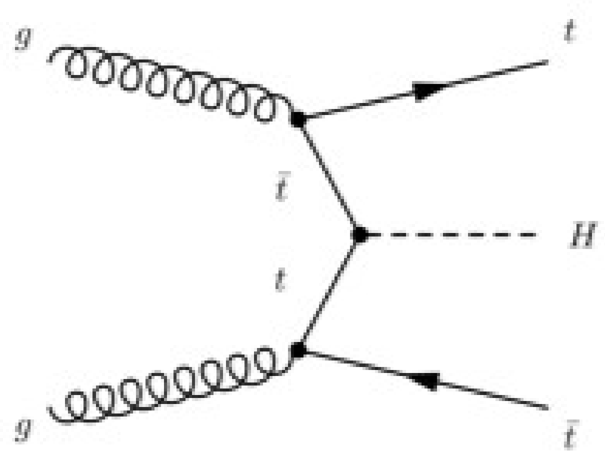


NLO predictions for associated production processes and prospects for full LHC programme

Roentsch and Schulze, arXiv:1501.05939 [hep-ph], JHEP 1407 (2014) 091

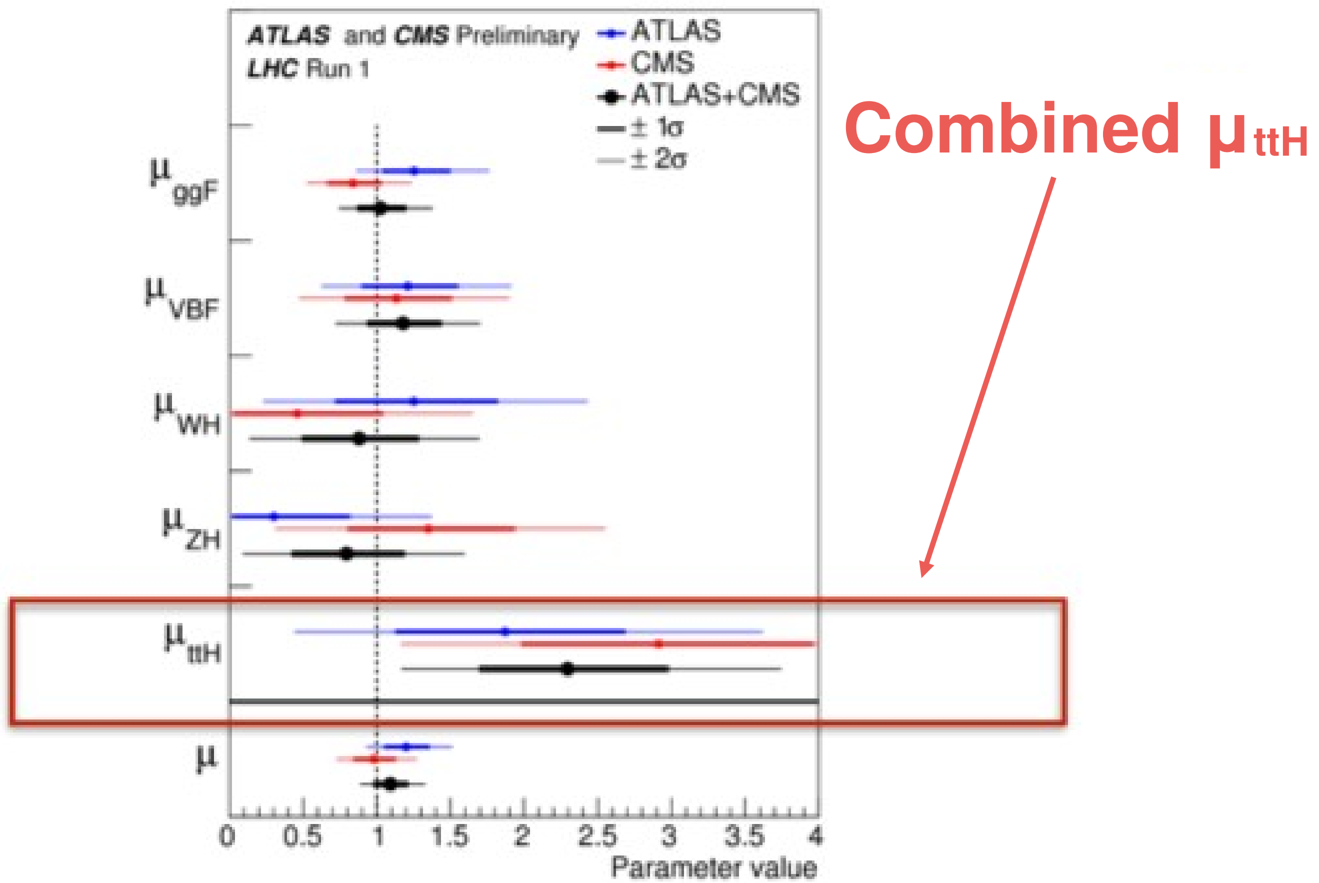
See also: Cen Zhang, this workshop

Current status: Yukawa Coupling



ttH searches have been **performed** at the LHC in all main Higgs decay modes at 7 and 8 TeV:

- Best fit signal strength ($\mu = \sigma/\sigma_{SM}$)
  - $\mu_{ttH} = 1.9^{+0.8}_{-0.7}$ - *ATLAS*
  - $\mu_{ttH} = 2.9^{+1.0}_{-0.9}$ - *CMS*
  - $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$ - *Combined*
    - significance - 4.4σ obs (2.0σ exp)
- Combined upper limits on σ/σ_{SM}
  - 3.2 obs (1.4 exp) - ATLAS
  - 4.5 obs (1.7 exp) - CMS



Prospects for full LHC programme:

K_u → 14-15% (300/fb)

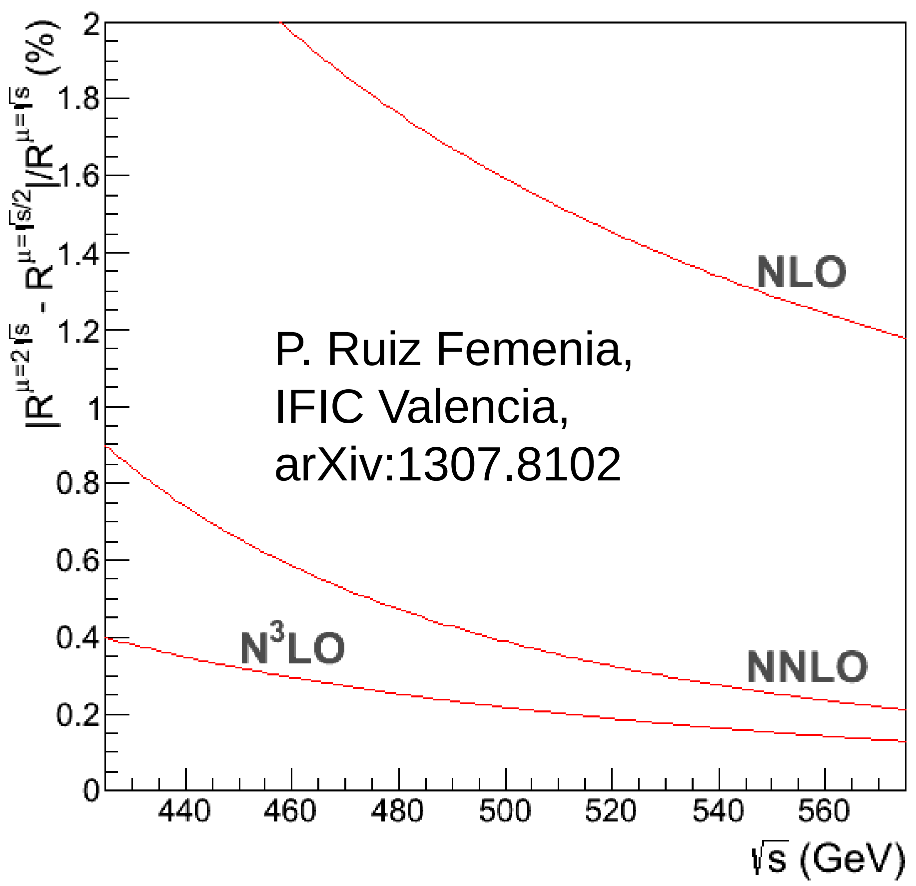
K_u → 7-10% (3000/fb) Snowmass Higgs report

Lepton colliders: precise predictions

For theory precision there is nothing like e^+e^-

Variation in x-section due to scale variations

Continuum
QCD corrections calculated to N^2LO
Scale variations at N^3LO estimated at ~ 0.3%.
Electroweak corrections are sizable, though.



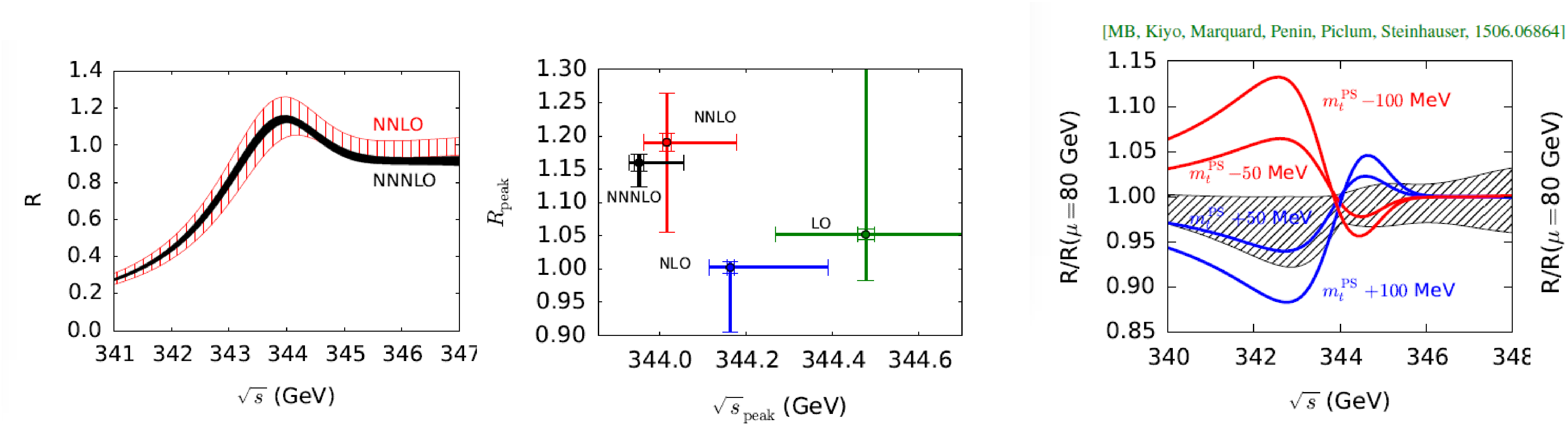
Needed: best, consensuated estimate of theory uncertainty versus √s

Parametric uncertainty:
Uncertainty on top mass/width propagates to x-sec:
→ 0.2% at 380 GeV
→ 0.1% at 420 GeV

Threshold theory

Beneke/Kiyo: N³LO description of $t\bar{t}$ production at threshold

Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864 [hep-ph]



Position shift for PS mass: 310 MeV (LO to NLO) 150 MeV (to NNLO) 64 MeV (to NNNLO)
Improvement of factor 3 in uncertainty in peak height.

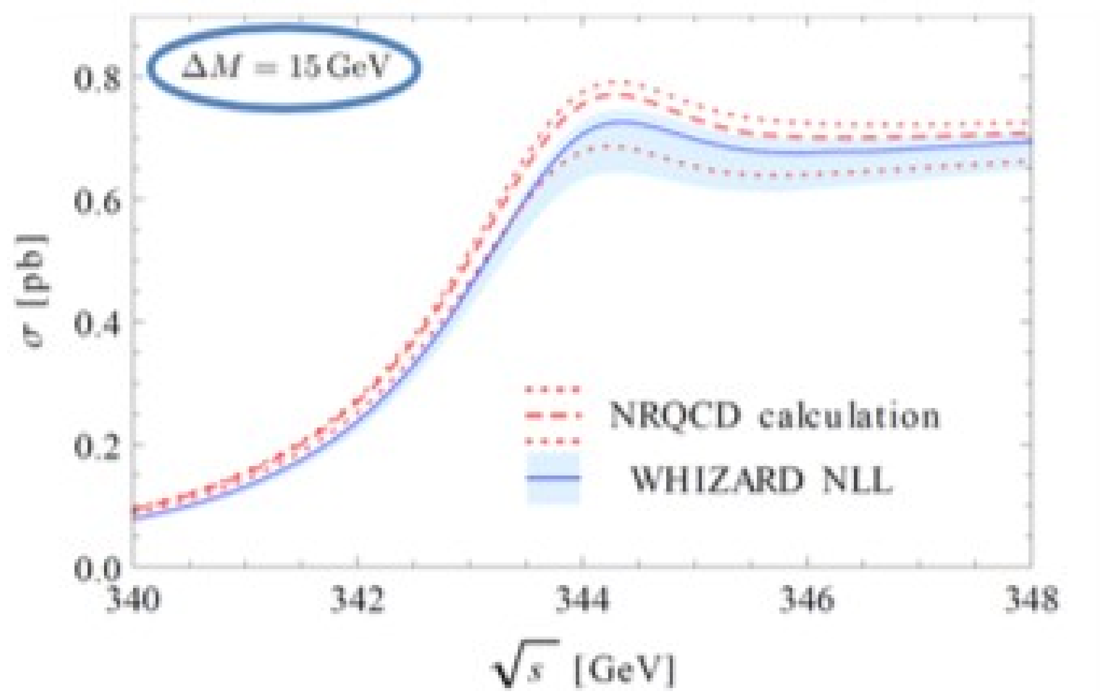
Alternative approach proposed by Kiyo/Mishima/Sumino: perform calcullation directly in terms of the $\overline{\rm MS}$ mass (corrections LO → NLO are large, but rapid convergence, final scale uncertainty seems smaller, arXiv:1506.06542)

See: Matthias Steinhauser, this workshop

Top pair threshold: MC status

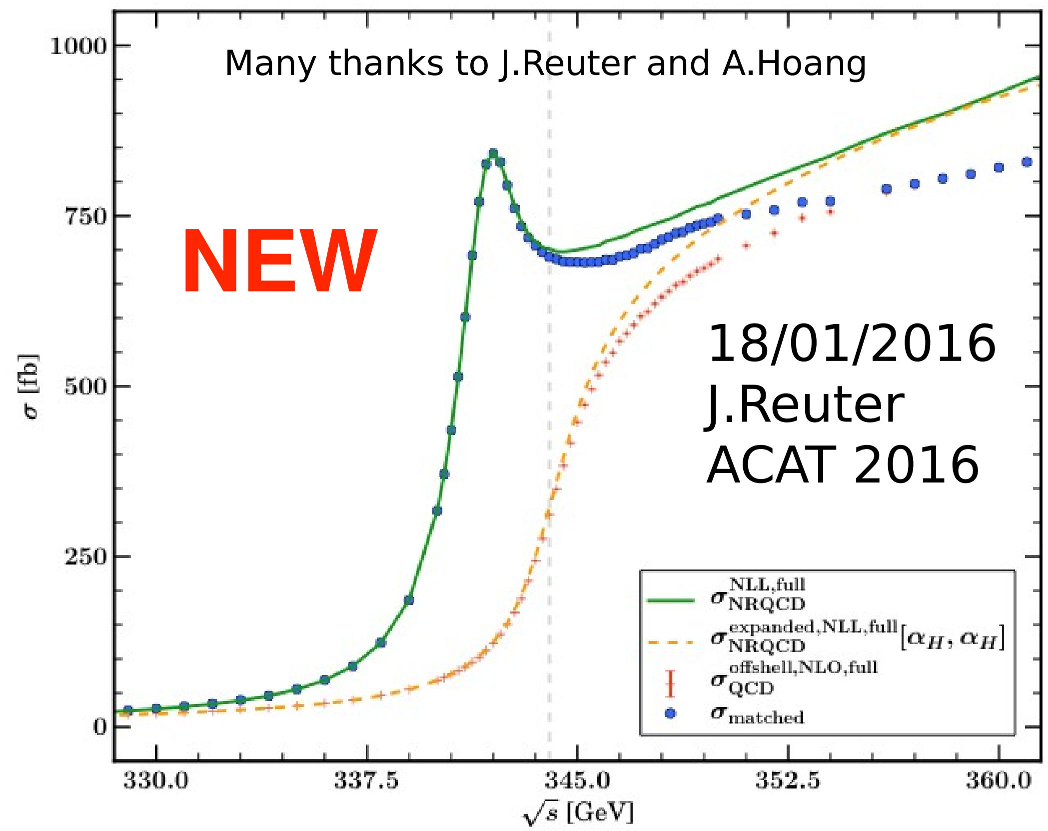
Now available: **NLO simulation of the ttbar threshold** in **WHIZARD** since version 2.2.3

More exclusive observables accesible
asymmetries, momentum distribution
Trivial incorporation of experimental reality: ISR and luminosity spectrum

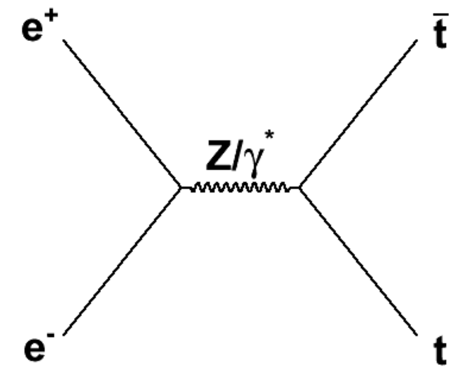


Match threshold & continuum calculations
- Matching procedure in place
- Uncertainty vs. √s in progress

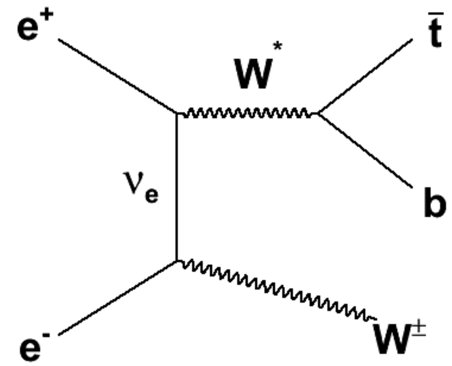
See: Jürgen Reuter, Matthias Steinhauser



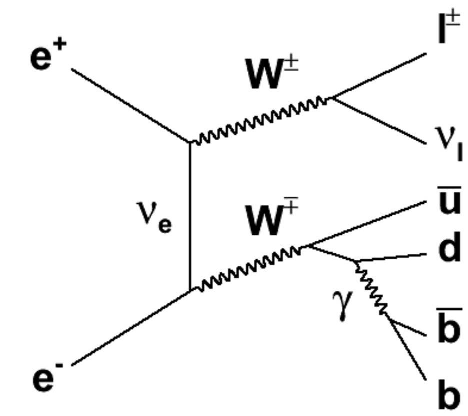
Challenge: selection



Top quark pair production...



...Single top quark production...



...WWγ/Z/h...

Maximum x-section for pair production ~0.6 pb

peak well above threshold ~ 420 GeV

Drop in (s-channel) cross-section at higher $\sqrt{s}$

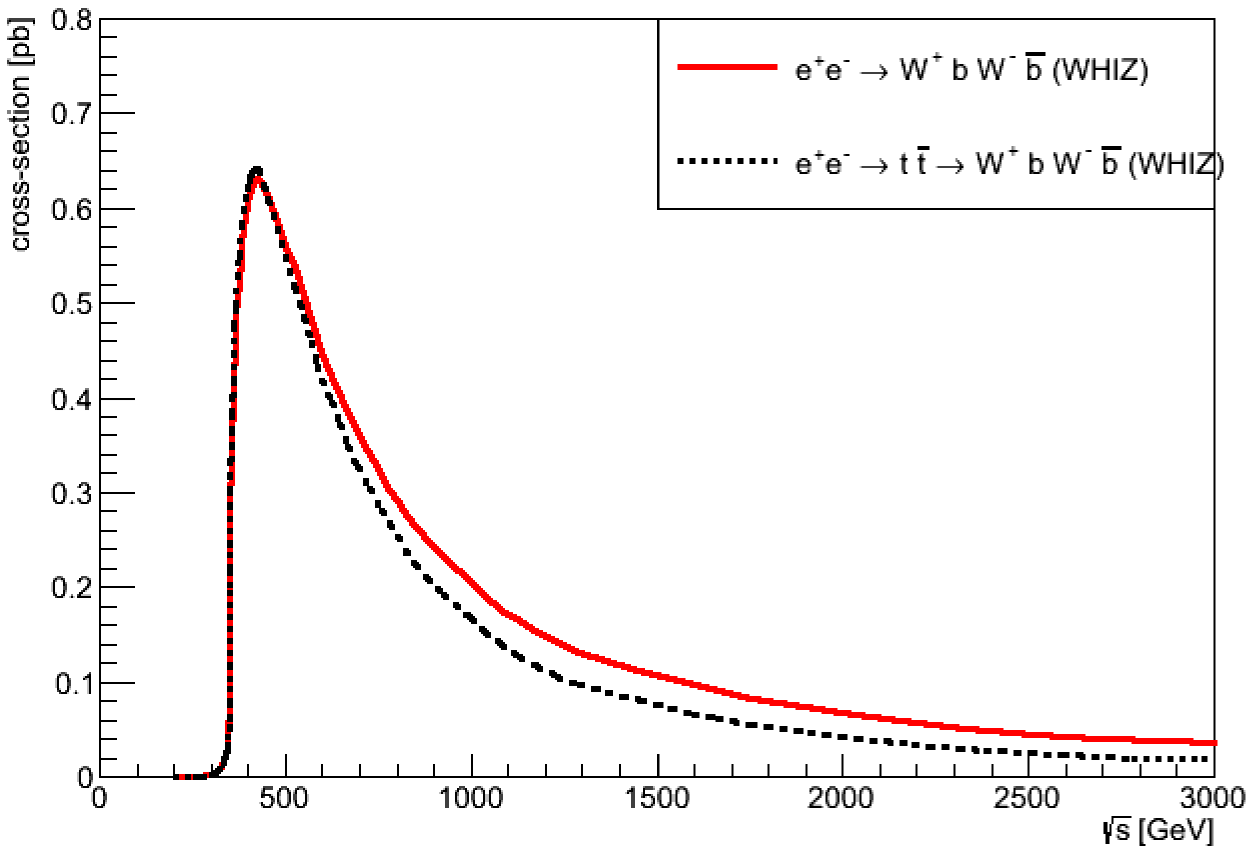
partially compensated by higher luminosity

$e^+e^- \rightarrow WbW\bar{b} \rightarrow$ 6 fermions is "contaminated" by single top production:

380 GeV: ~5%
500 GeV: ~9%
3 TeV: ~50%

As far as we can (at 500 GeV) single top is ~indistinguishable from pair production

See: *Garcia, Perello, Ros, Vos, Study of single top production at high energy electron-positron colliders, arXiv:1411.2355*



Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

Challenge: reconstruction

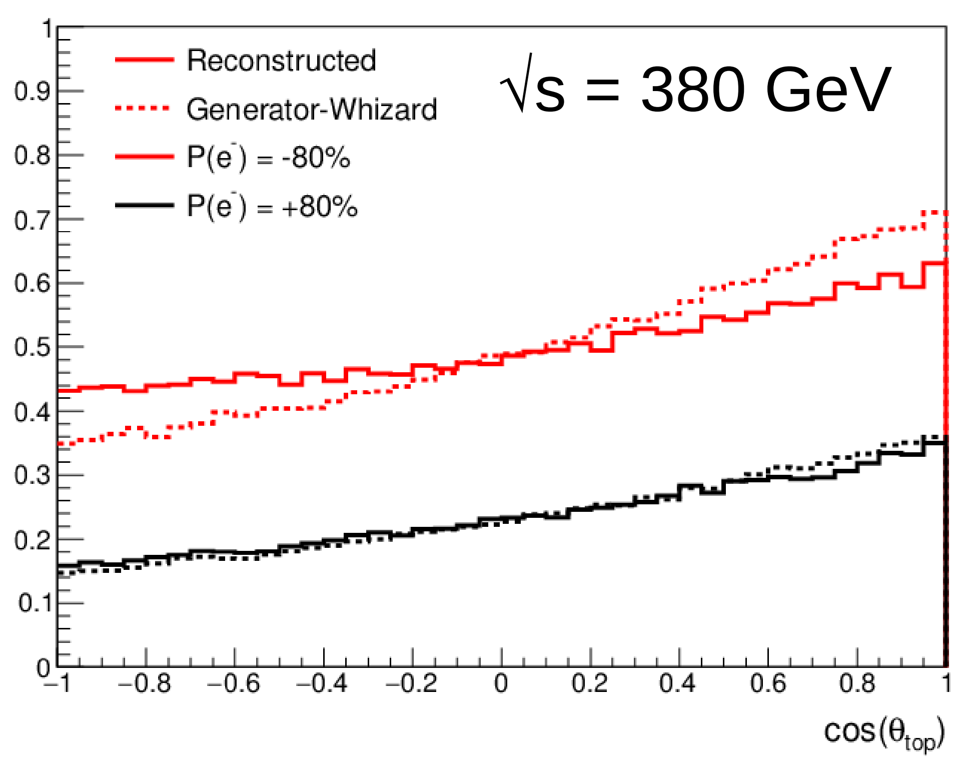
$t\bar{t}$ pairs at rest form a quite different final state than in at 500 GeV

- Full simulation results for CLIC@380 appearing (CERN + IFIC)

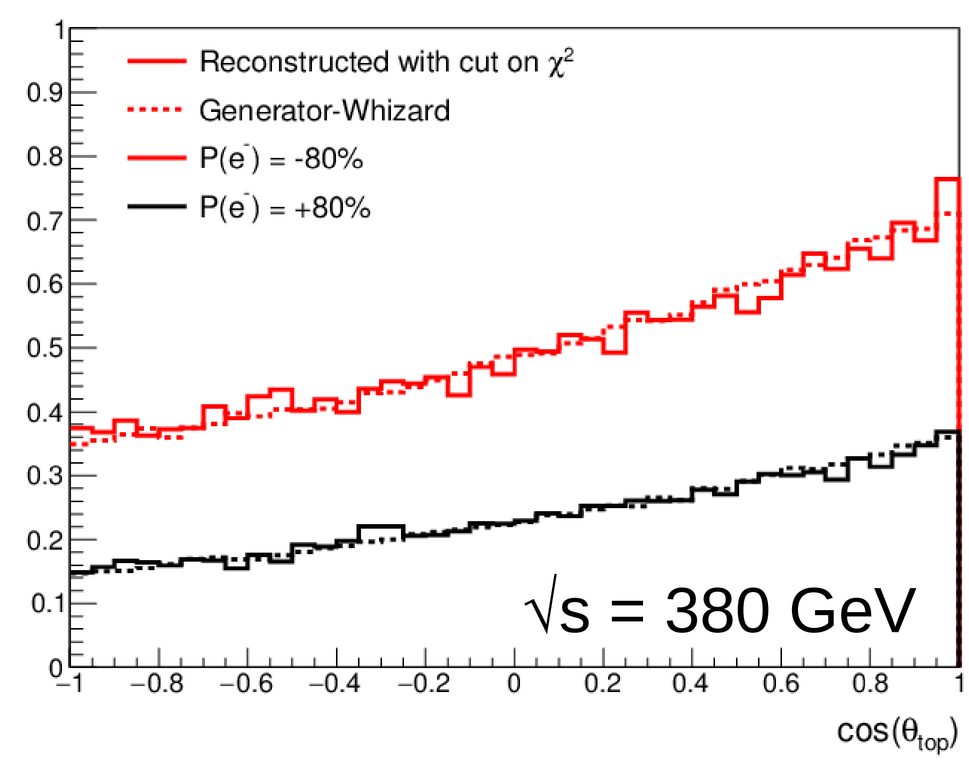
- A_{FB} much smaller and migrations due to ambiguity in b-W pairing more severe at 380 GeV than at 500 GeV (esp. for -80%, +30% polarization)

- Turning the crank on the usual machinery – a very tight cut on reconstruction quality – works at a rather high prize in statistics (and quite possibly modelling systematics)

Full simulation, “standard” reconstruction



Same + cut on reconstruction quality χ^2

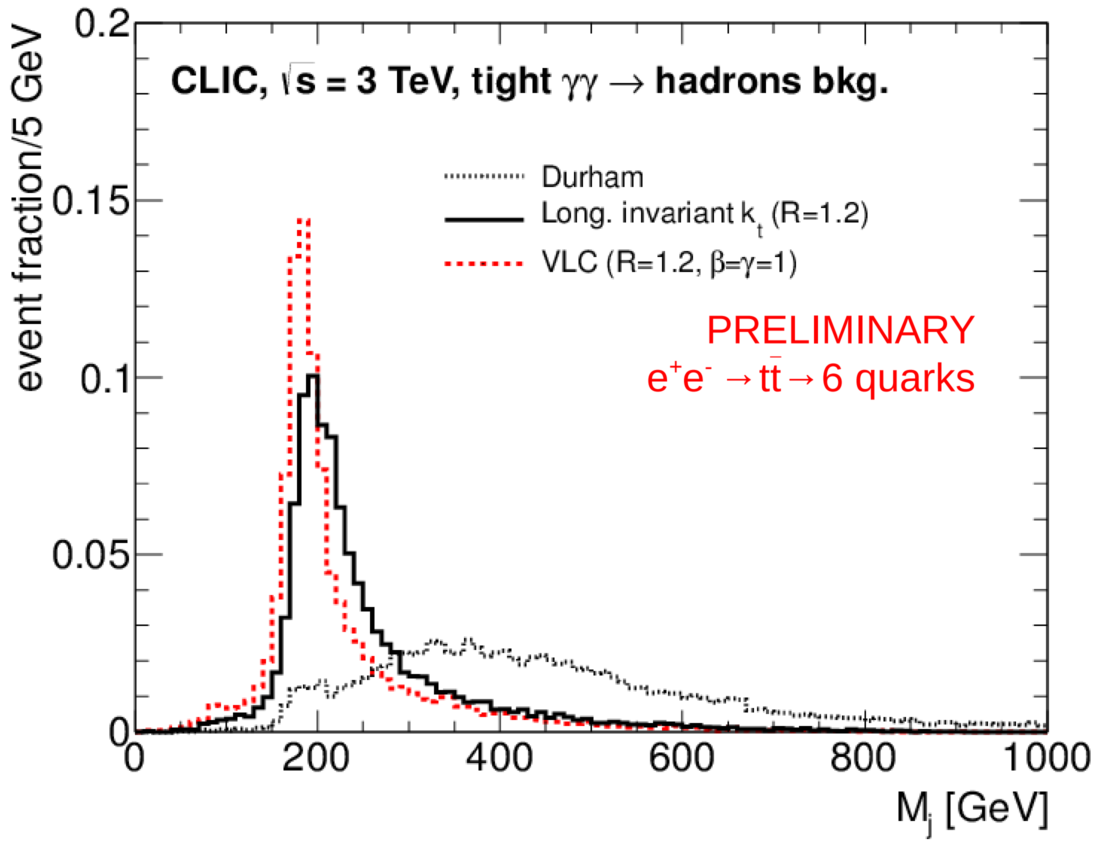


Challenge: Boosted top quarks

TeV top quarks in CLIC high energy phase are “an entirely different beast”

- available statistics
  - s-channel process: drop in x-section not compensated by increase in luminosity
- selection
  - What to do with the low-energy tail due to ISR and beam energy spread tail?
  - Top-tagging: very striking signal, small backgrounds → high efficiency?
  - Fat jet substructure to replace fermion counting? ($t\bar{t}$ – WW – $q\bar{q}$ separation)
- reconstruction
  - no ambiguity for highly boosted tops

systematic comparison just starting



FCNC top decays: t → cH

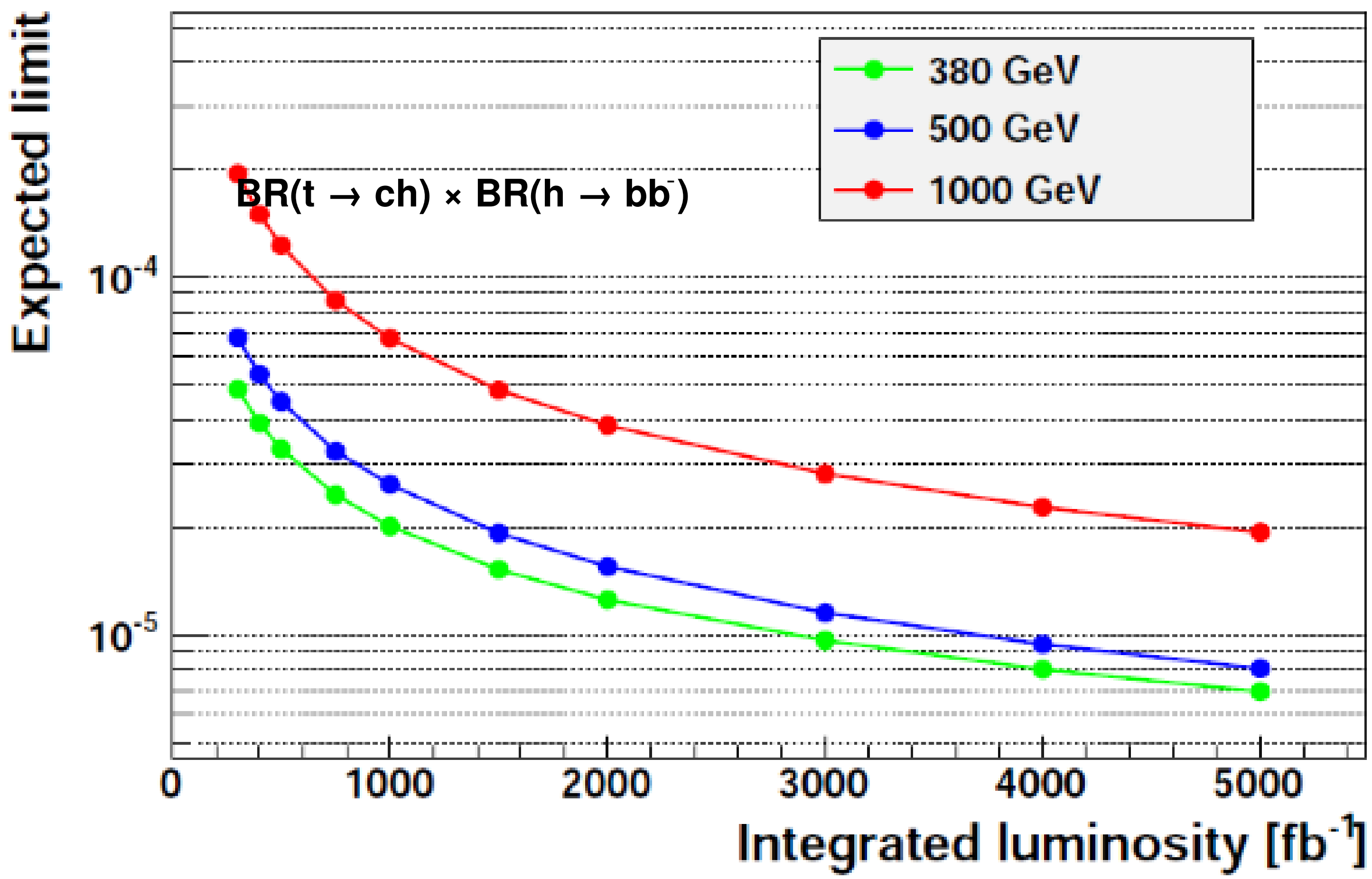
F. Zarnecki: **Measurement of FCNC top decays at ILC/CLIC studied at parton level**.

Top workshop Valencia July 15
https://indico.cern.ch/event/381148/session/5/contribution/4/attachments/759420/1674930/toplc2015.pdf

Decay t→c h is most interesting:

- well constrained kinematics
- test of Higgs boson couplings
- seems to be most difficult for LHC

Two Higgs Doublet Model (2HDM) as a test scenario

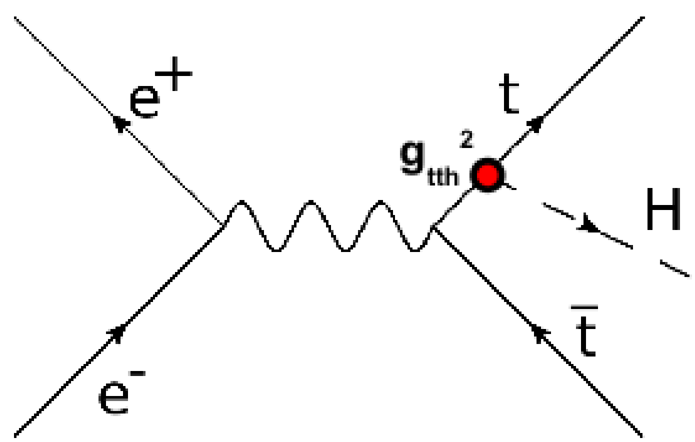


Expected limits on BR(t → ch) × BR(h → bb̄) ~ 10^{-5}
depending on the energy, luminosity and detector parameters in a H-20 LC full program

Order of magnitude improvement wrt Snowmass expectation for LHC + lumi upgrade

Top Yukawa coupling: ttH at LC

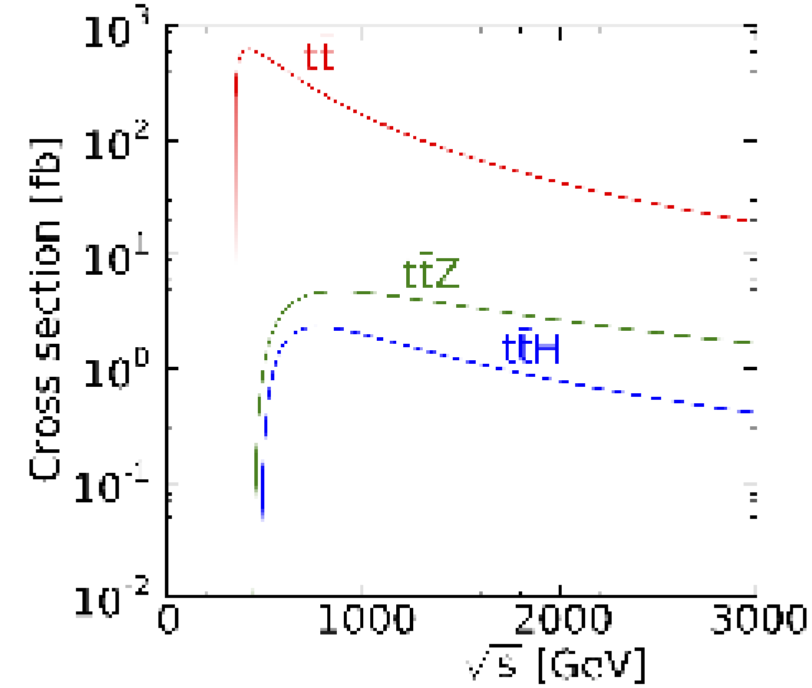
The top Yukawa coupling g_{tth} can be measured directly



$$\frac{\Delta g_{ttH}}{g_{ttH}} = c \cdot \frac{\Delta \sigma}{\sigma}$$

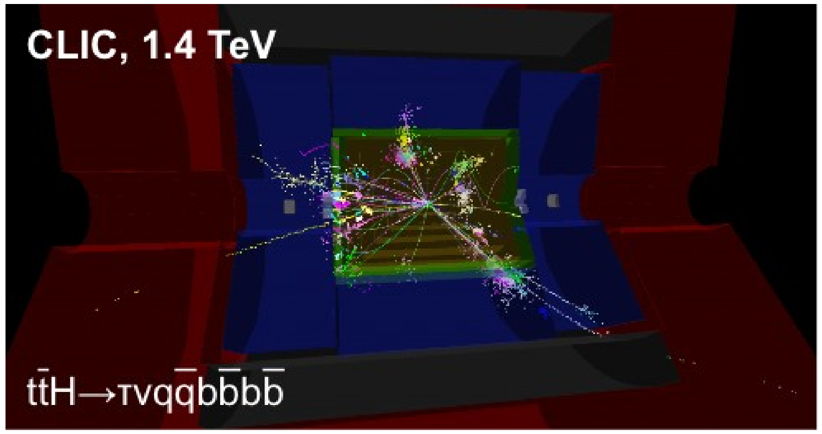
No Higgsstrahlung: c = 0.50
ILC 1 TeV: c = 0.52
CLIC 1.4 TeV: c = 0.53

Broad maximum around 800GeV



Recent studies based on full detector simulation

500 GeV, ILC (ILD):
Yuji Sudo
1 TeV, ILC (ILD & SiD):
Tony Price, Ph.R.,
Jan Strube, Tomohiko Tanabe
1.4 TeV, CLIC (CLIC_SiD):
Sophie Redford, Ph.R., Marcelo Vogel



About 4% precision on the top Yukawa coupling achievable with $1ab^{-1}$

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	(14 – 15)%	(7 – 10)%	10%	4%	4%

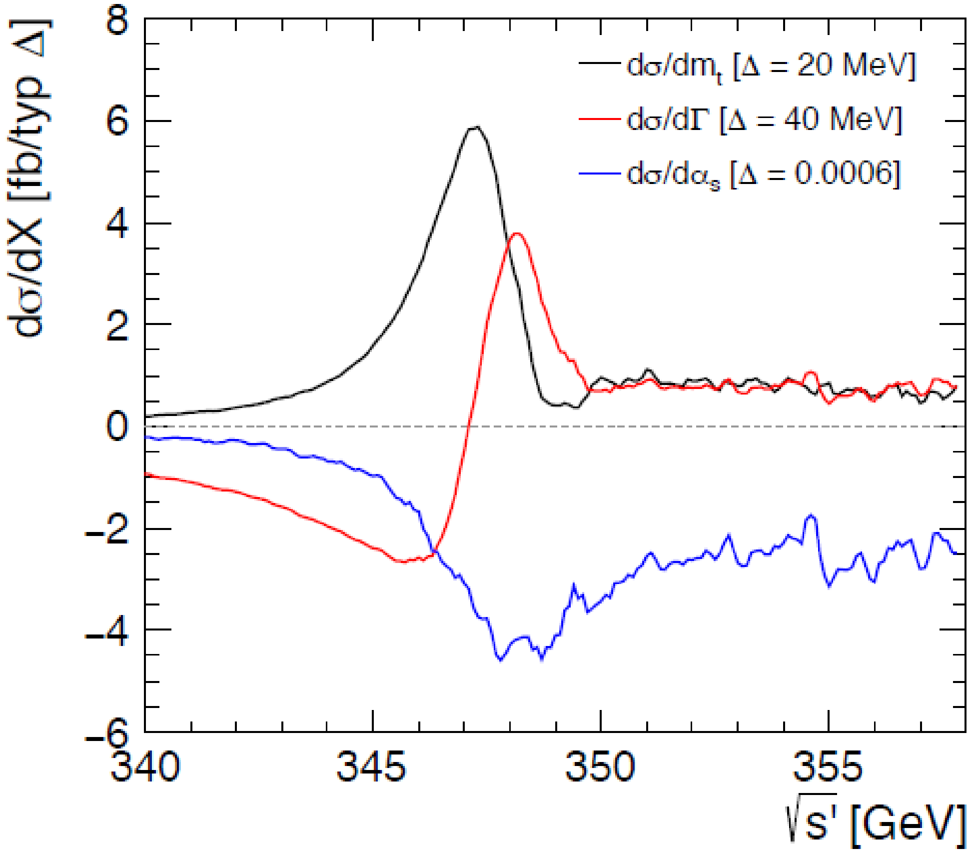
from
arXiv:1311.2028

Talk by Ph.Roloff at TopLC 2015 - Valencia

Top mass from threshold scan

Threshold shape depends strongly on mass & width.
Normalization sensitive to α_s and top Yukawa coupling.

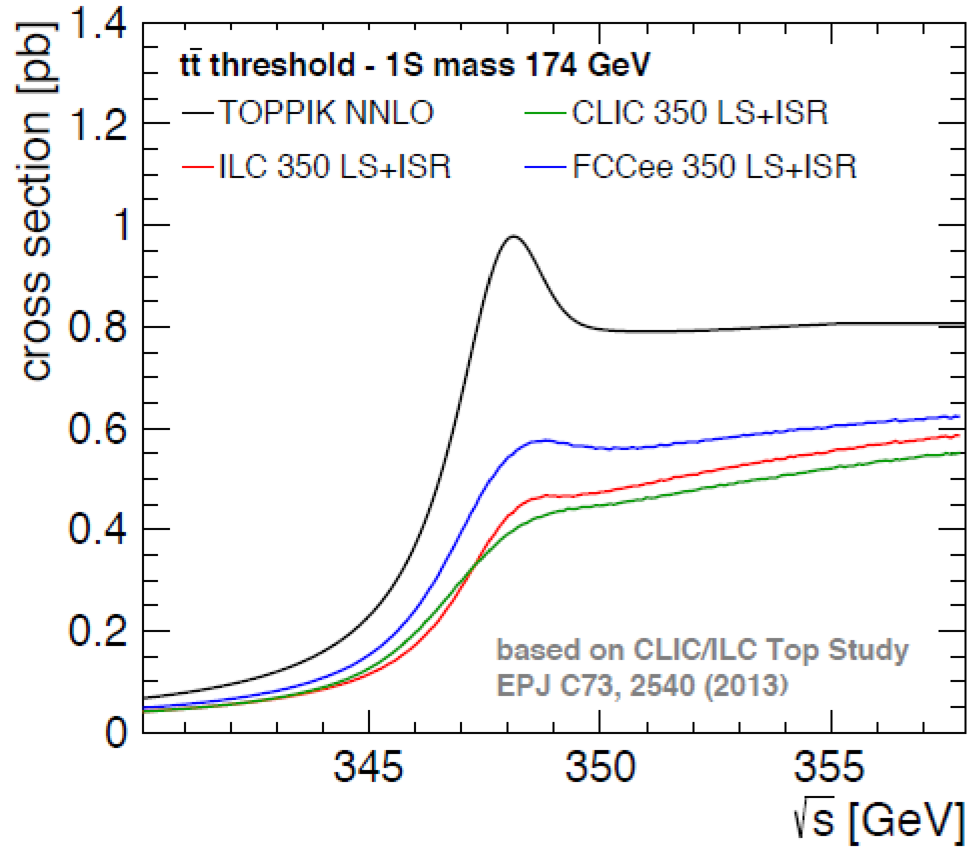
Kuhn, Acta Phys.Polon. B12 (1981) 347



Extract 1S/PS mass from scan (10 x 10/fb):

Martinez, Miquel, EPJ C27, 49 (2003)
Seidel, Simon, Tesar, Poss, EPJ C73 (2013)
Horiguchi et al., arXiv:1310.0563

Minor differences due to beam energy spectra of ILC, CLIC and FCC-ee
Luminosity spectrum can be precisely reconstructed using



Systematic uncertainties - theory

Extract mass with NNNLO calculation:

30 MeV theory uncertainty on 1S mass (M. Beneke/F. Simon, in progress)

Theory uncertainty in conversion from 1S to $\overline{\text{MS}}$ scheme:

3-loop calculation → ~100 MeV

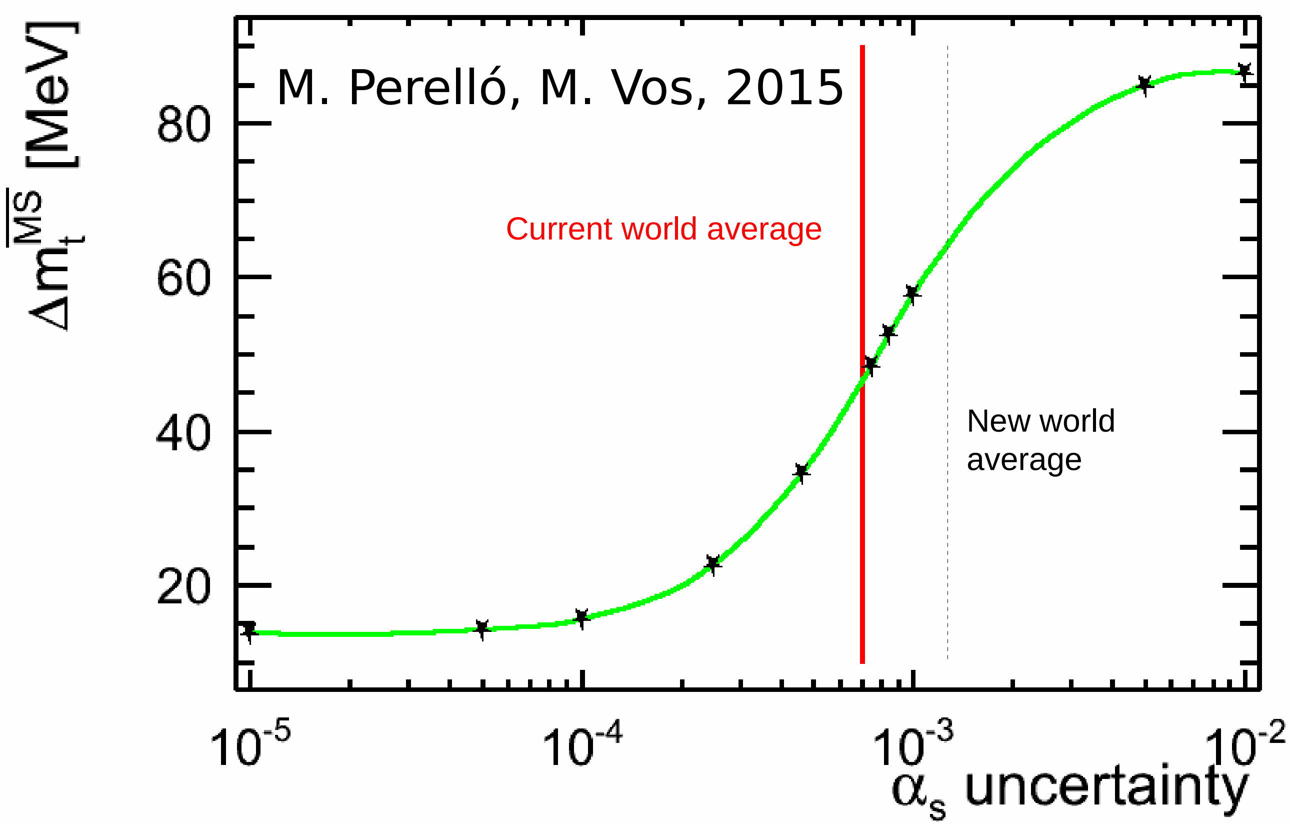
4-loop calculation → <10 MeV

(P. Marquard et al., arXiv:1502.01030, PRL114 (2015))

Uncertainty on strong coupling constant strikes twice:

- as a degree of freedom in the fit to extract 1S mass (δM^{1S} goes from 12 MeV → 42 MeV)
- as a parametric uncertainty in the 1S → $\overline{\text{MS}}$ conversion

Top quark mass precision vs. prior knowledge of strong coupling strength



Top mass uncertainties

Statistical uncertainty:

Assuming 10x10 fb^{-1} → 18 MeV *(F. Simon, LCWS15)*

(depending on polarization and fit details several authors find 16-30 MeV)

Experimental systematic uncertainties:

5% uncertainty non-$t\bar{t}$ bkg → 18 MeV *(Seidel, Simon, Tesar, Poss)*

Single top "contamination" → < 30 MeV *(Boronat et al.,arXiv:1411.2355)*

10^{-4} precision on $\sqrt{s}$ → 30 MeV *(Seidel, Simon, Tesar, Poss)*

Realistic uncertainty on lumi-spectrum → 10 MeV *(Sailer & Poss, EPJC (2014) 74:2833, F. Simon, AWLC14, arXiv:1411.7517)*

Theory uncertainty in 1S mass extraction:

Evaluation at NNNLO → 32 MeV? *(F. Simon, LCWS15)*

Theory uncertainty from MS mass conversion:

4-loop calculation → 10 MeV? *(Marquard et al.)*

α_s parametric uncertainty → 12-42 MeV *(M. Perelló)*

With some faith in the progress of lattice QCD, 50 MeV seems like a reasonable goal
A quark mass to a precision of 3 parts in 10.000!!!

Yukawa at threshold

Ishikawa et al., arXiv:1310.0563:

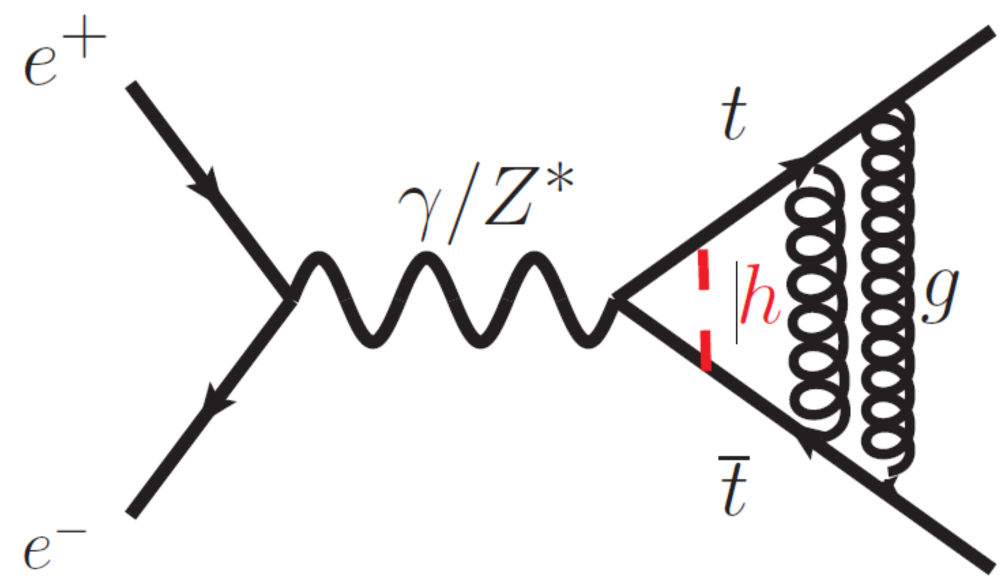
consider several observables (σ, A_{FB}, p)

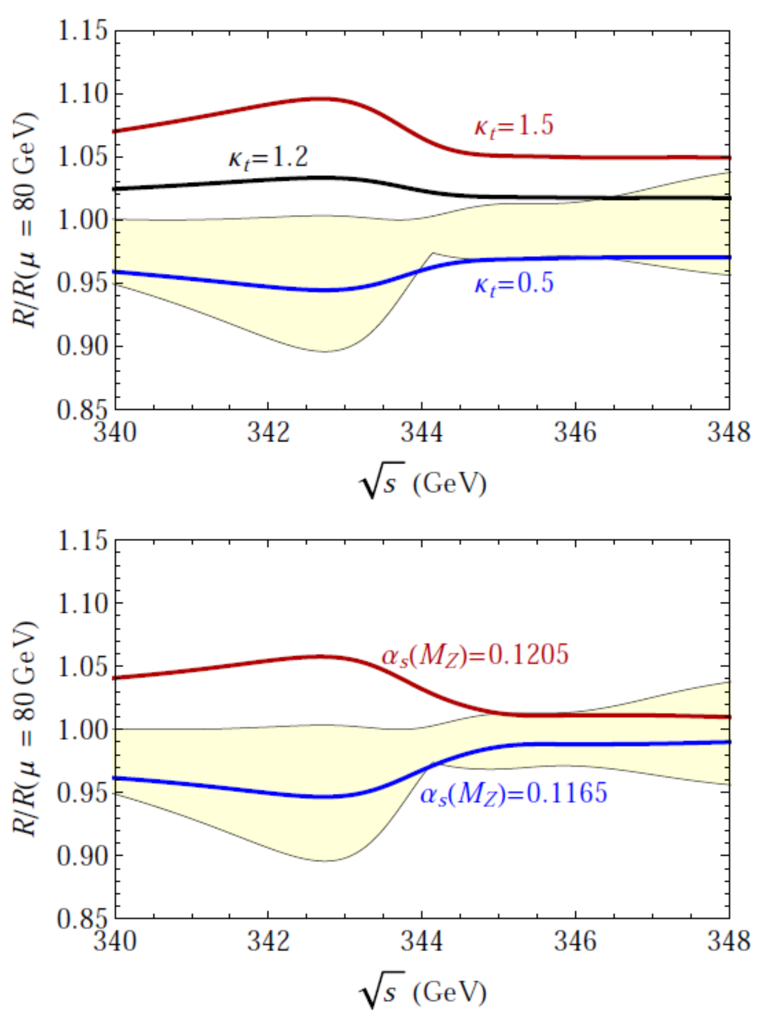
two polarizations, 220 fb^{-1} in total

extract properties from simultaneous fit

- ΔM ~ 16 MeV
- $\Delta\Gamma$ ~ 21 MeV
- Δy ~ 4.2 %

Stat. Uncertainty only





Enhancement of 9%

~ independent of √s... no shape information...

Feature is nearly degenerate with α_s

Have to assume very good α_s

NNNLO uncertainty approx. 3%

Theory uncertainty today: 18%

Beneke et al., Nucl. Phys. B899 (2015) 180-193: "Our results show that once theoretical uncertainties are taken into account, it is unlikely that such a high precision [i.e. 4.2%] can be achieved."

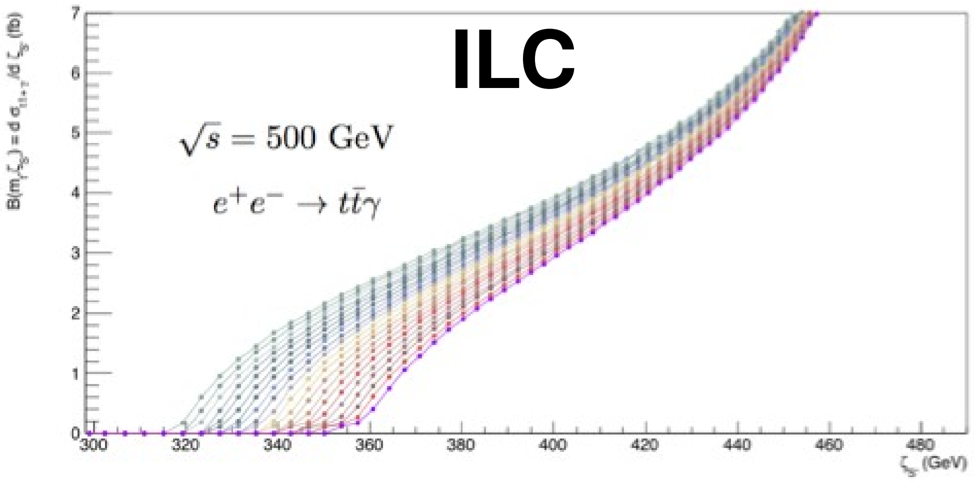
Top mass measurements: Alternative techniques

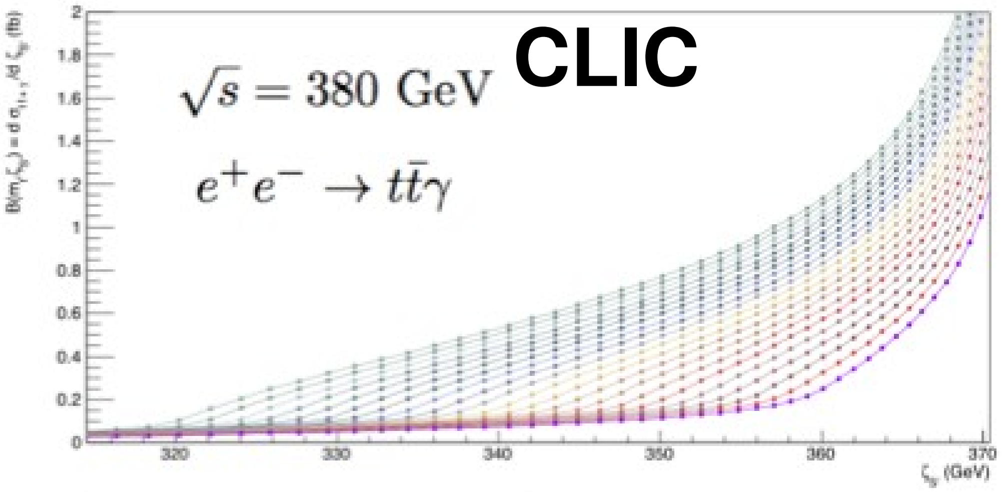
LC scenarios start above threshold (ILC@500GeV, CLIC@380GeV) → first measurement top mass

Extraction of the top quark mass from the differential tty and ttg cross-section versus s'

Precision seems competitive for √s ~ 400 GeV *Boronat, Fuster, Gomis, in preparation*

(cf. m(b) at m(Z) at LEP, EPJC73 (2013) 2438, ATLAS-CONF-2014-053)

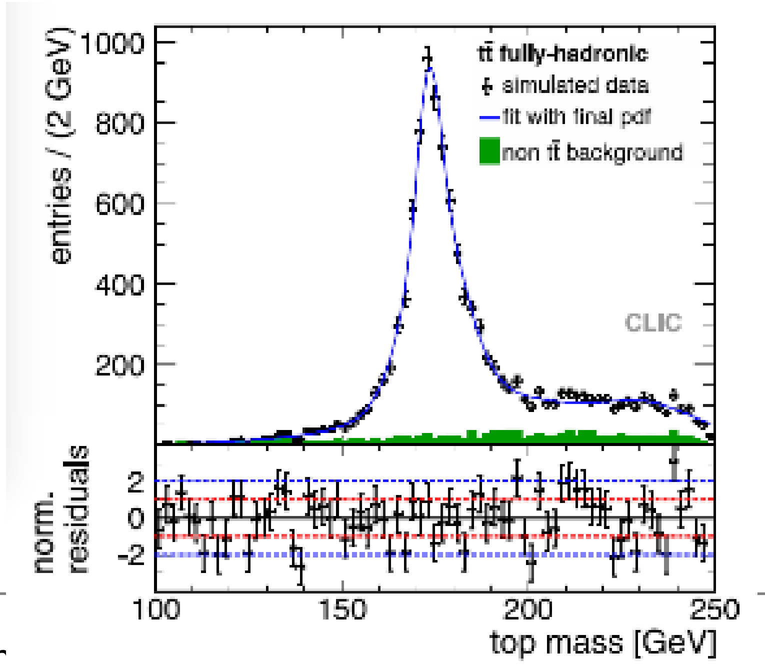




Conventional measurement on top decay products

80 MeV stat. precision at 500 GeV
→ input to clarify MC mass interpretation

Seidel, Simon, Tesar, Poss, EPJ C73 (2013)



Top quark couplings: TDR times

measure

$\sigma(+) \quad A_{FB}(+)$

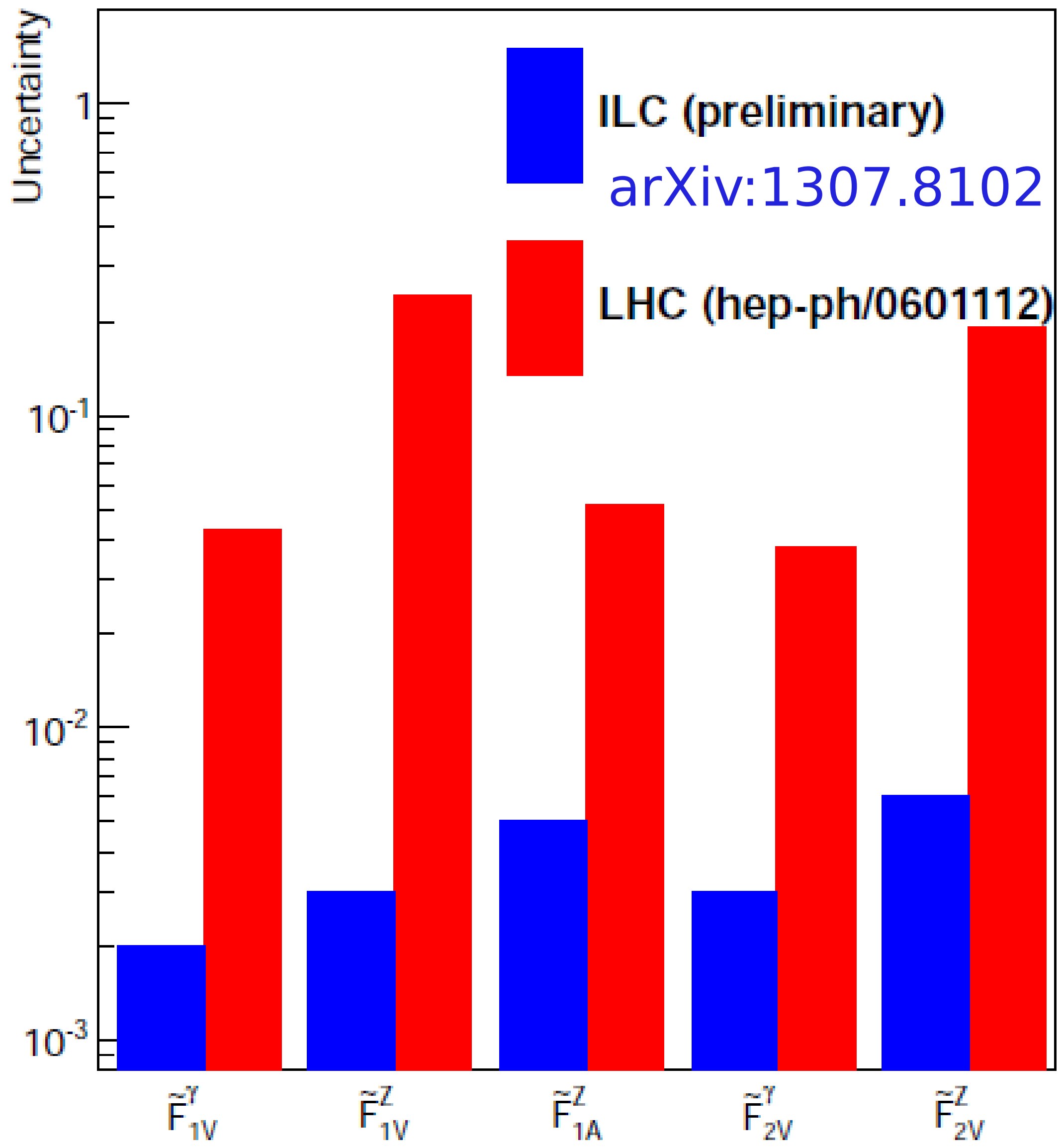
$\sigma(-) \quad A_{FB}(-)$

extract

$$\left.\begin{matrix}(+ = e^-_R) \\ (- = e^-_L)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F^{\gamma}_{1V} & * & F^{\gamma}_{2V} \\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V}\end{matrix}\right\}$$

Measure 2 observables
for 2 beam polarizations:
- x-section
- FB asymmetry

Extract form factors in groups
(assuming SM for remaining groups)



Assumptions:

LHC: 14 TeV, 300/fb
LC: √s = 500 GeV, L = 500/fb
$P(e^-)$ = +/- 80%, $P(e^+)$= -/+ 30%
$\delta\sigma$ ~ 0.5% (stat. + lumi)
δA_{FB} ~ 1.8% (stat., covers systematics?)

Polarization needed to disentangle photon and Z-boson form factors!

Especially for ttZ LC precision is better than existing (model-dependent) limits from top decay, LEP T-parameter, B-factories (full comparison in progress)

BSM sensitivity vs. √s

Impact of new physics on cross-section and asymmetries depends on **√s**

$$\Gamma^{\mu}_{t\bar{t}(\gamma,Z)} = ie\left[\gamma^{\mu}\left[\widetilde{F}^{\gamma,Z}_{1V} + \widetilde{F}^{\gamma,Z}_{1A}\gamma^{5}\right] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}\left[\widetilde{F}^{\gamma,Z}_{2V} + \widetilde{F}^{\gamma,Z}_{2A}\gamma^{5}\right]\right]$$

BSM impact on cross-section and A_{FB} increases strongly with √s for axial dipole moments and four-fermion operators;

→ factor 10 and more between 0.5 and 3 TeV

Much less pronounced increase for vector dipole moments, none for $F^{\gamma,Z}_{1V/A}$

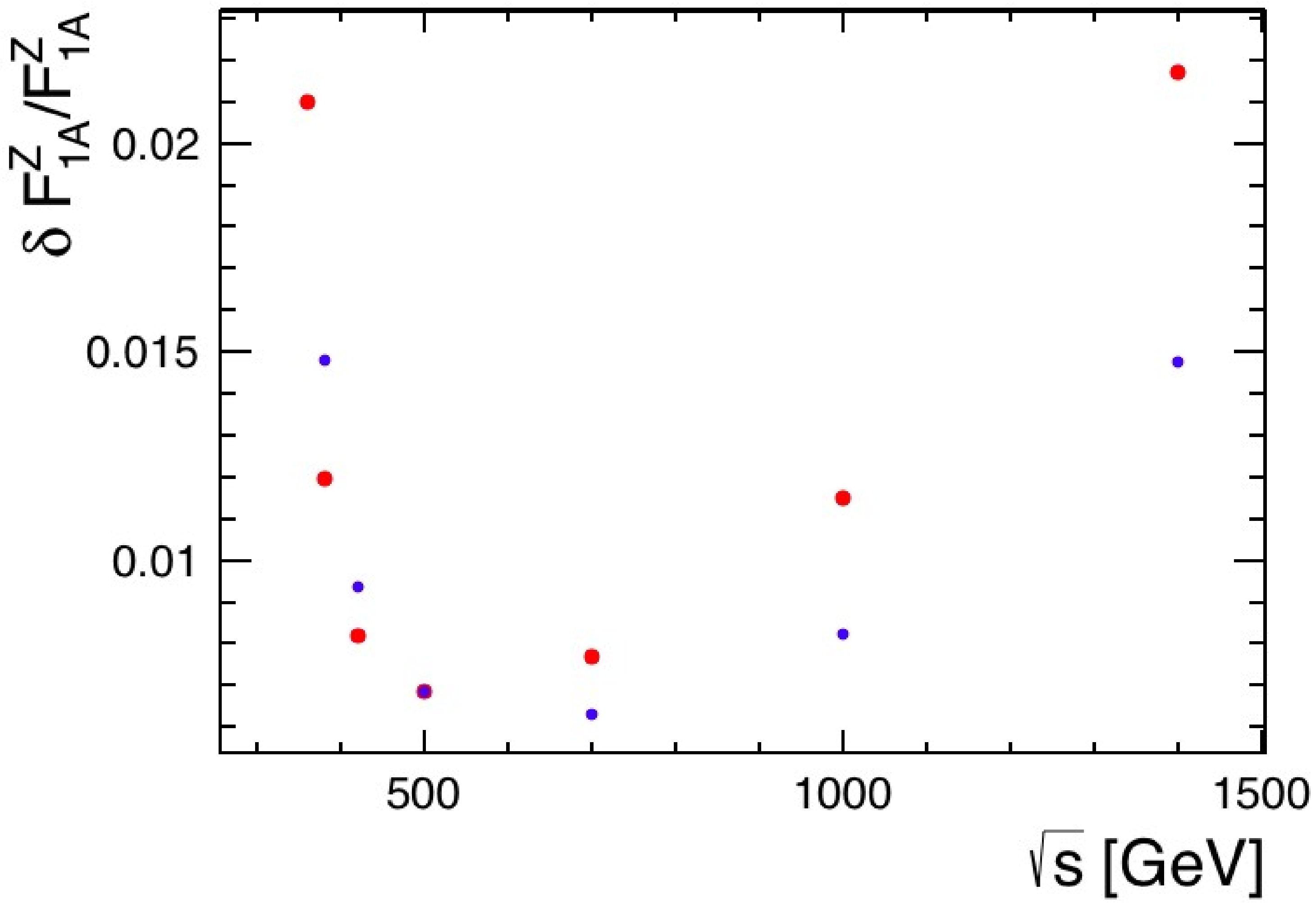
For details, see talk in CLIC workshop, CERN, January 2015:
https://indico.cern.ch/event/336335/session/1/contribution/174

Top quark couplings: sensitivity vs. sqrt(s)

● Luminosity proportional to √s ● Flat Luminosity: 500/fb

Small cms energies:

- Vanishing axial vector coupling
  +
- Lumi decreases at linear colliders



High cms energies:

- Quickly decreasing cross section
- ... partially compensated by increasing luminosity

From Roman Poeschl, Wednesday top session

- F1AZ profits from somewhat higher energies (beta dependence)
- Remark: Full disentangling for F1VZ and F2VZ at ~1 TeV

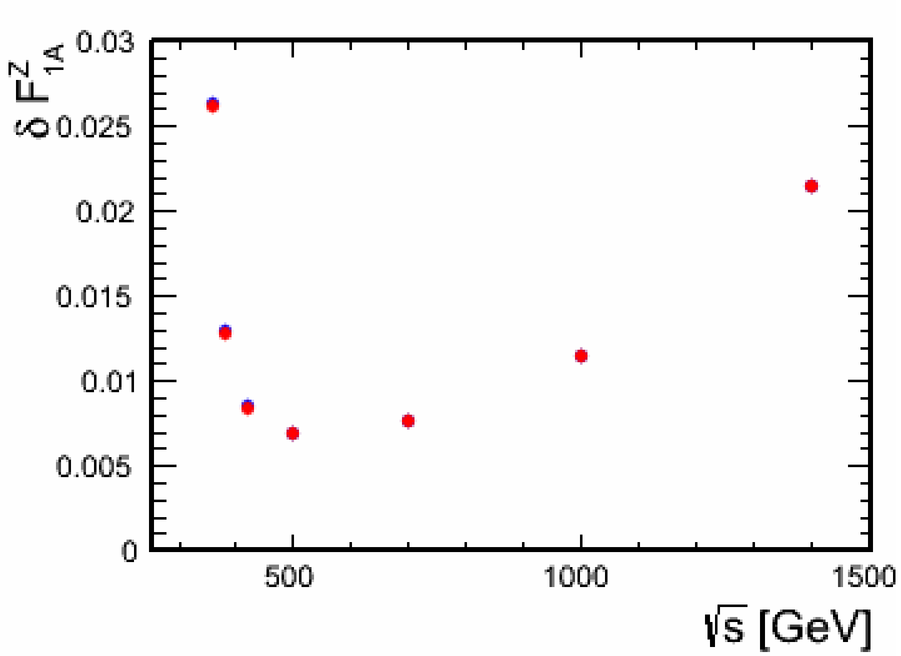
√s ~ 1 TeV attractive option

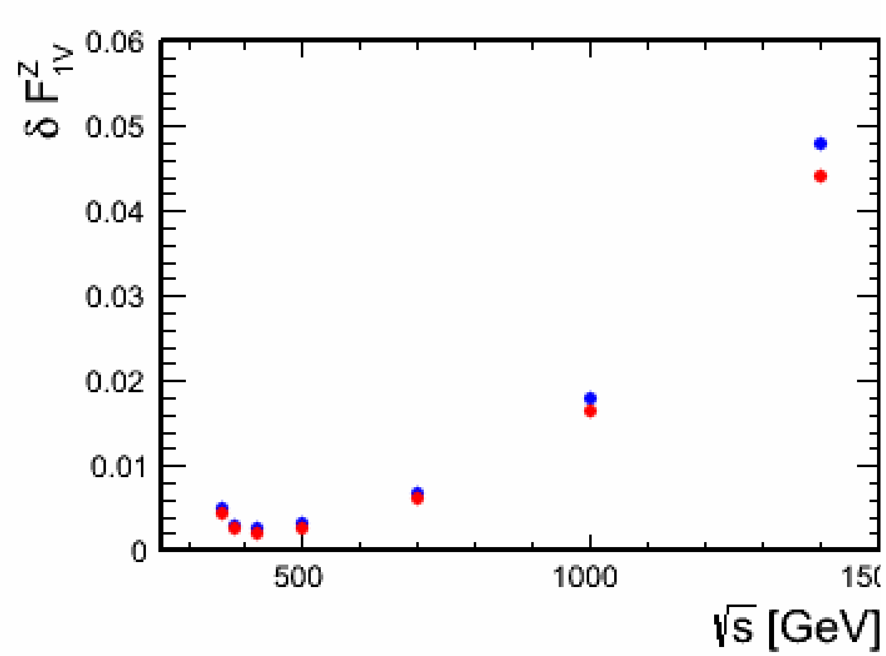
Top quark couplings: sensitivity vs. sqrt(s)

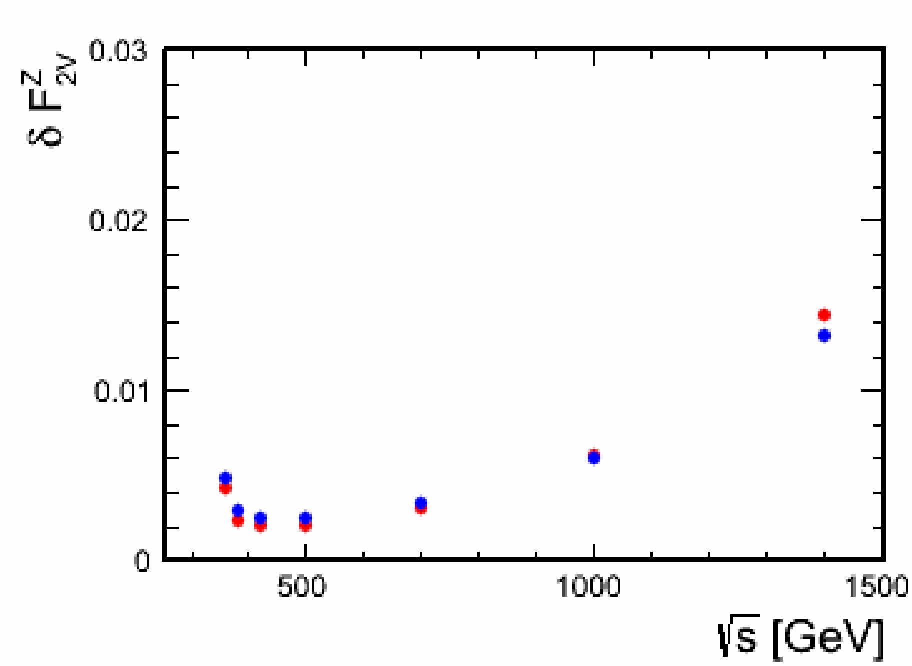
Simple evaluation of statistical uncertainty. A thorough full-simulation CLIC study started.

stat. dominated uncertainty:
$\delta\sigma/\sigma \sim 1/\sqrt{N}$ $\delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$
Integrated luminosity: 2 x 250/fb

Nominal beam polarization (e^- 80%, e^+ 30%)
Electron polarization only







F_{1V}: shallow minimum → *optimal around 400 GeV*
F_{1A}: A_{FB} degraded strongly close to threshold → *500 GeV*
F_{2V}: impact of new physics grows strongly with energy → 1-3 TeV

Truly optimal: comprehensive program at several energies

Top quark couplings: Results

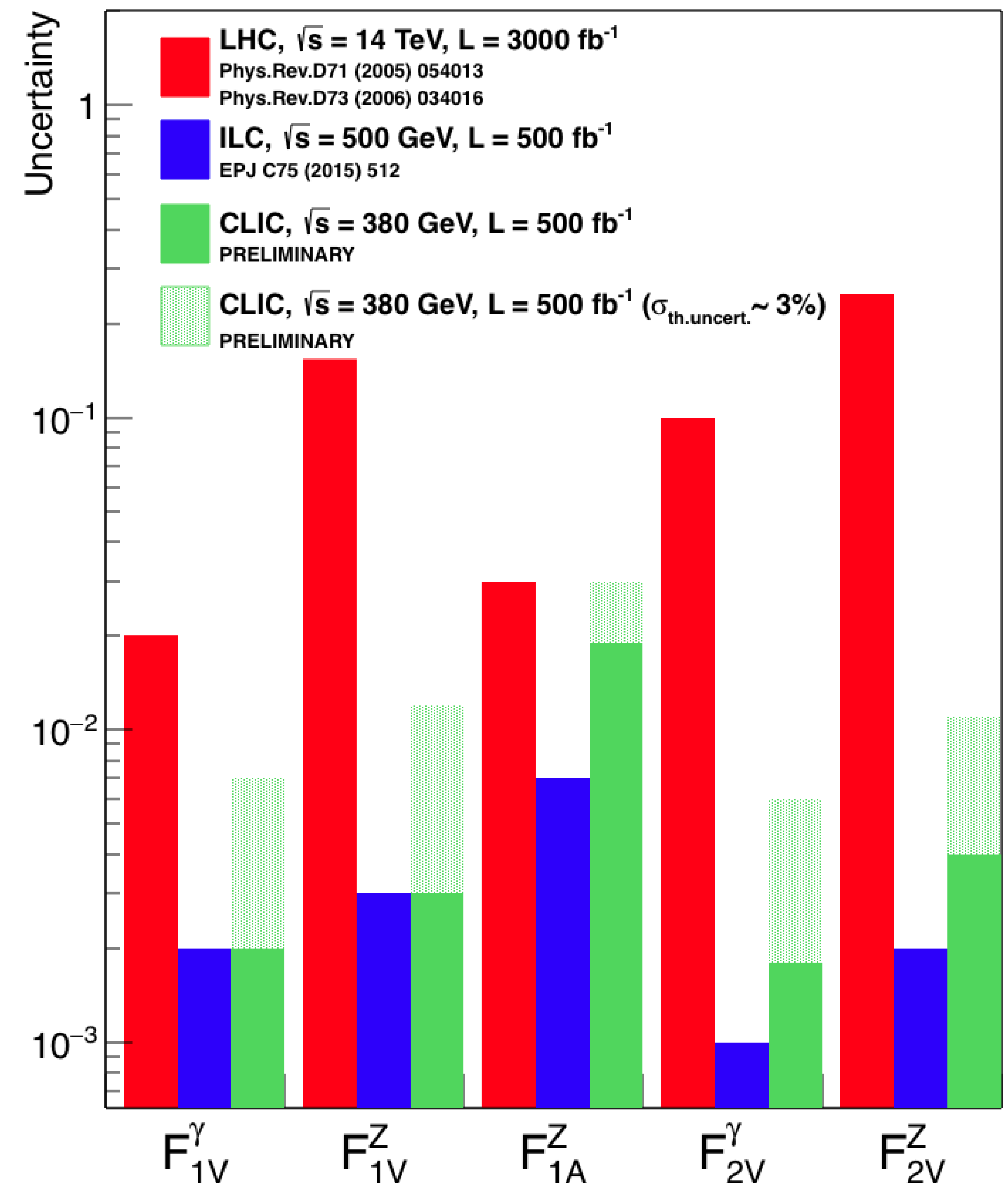
ILC@500GeV L=500fb^{-1}

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{\text{FB}}/A^t_{\text{FB}})_{\text{stat.}}$ (%)
−0.8, +0.3	0.47	1.8
+0.8, −0.3	0.63	1.3

CLIC@380GeV L=500fb^{-1}

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{\text{FB}}/A^t_{\text{FB}})_{\text{stat.}}$ (%)
−0.8, 0	0.47	3.8
+0.8, 0	0.83	4.6

$$\Gamma_\mu^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\},$$



CLIC: similar precision to ILC except for the coupling ***F_{1A}^Z*** that suffers the large statistical error of A_{FB} ~5%

Conservative scenario for CLIC: NNNL calculations at threshold predict a 3% theory uncertainty

ILC and **CLIC** can characterise the ttγ and ttZ vertices very precisely, **an order of magnitude better than LHC** prospects from associated production

Matrix element on di-lepton final state

Khiem, Kou, Kurihara, le Diberder, Probing new phyiscs using top quark polarization in the e+e- → tt process at future Linear Colliders, arXiv:1503.04247 [hep-ph]

GRACE six-fermion process without narrow-width approximation
(no ISR, no single top, no hadronization, no detector)

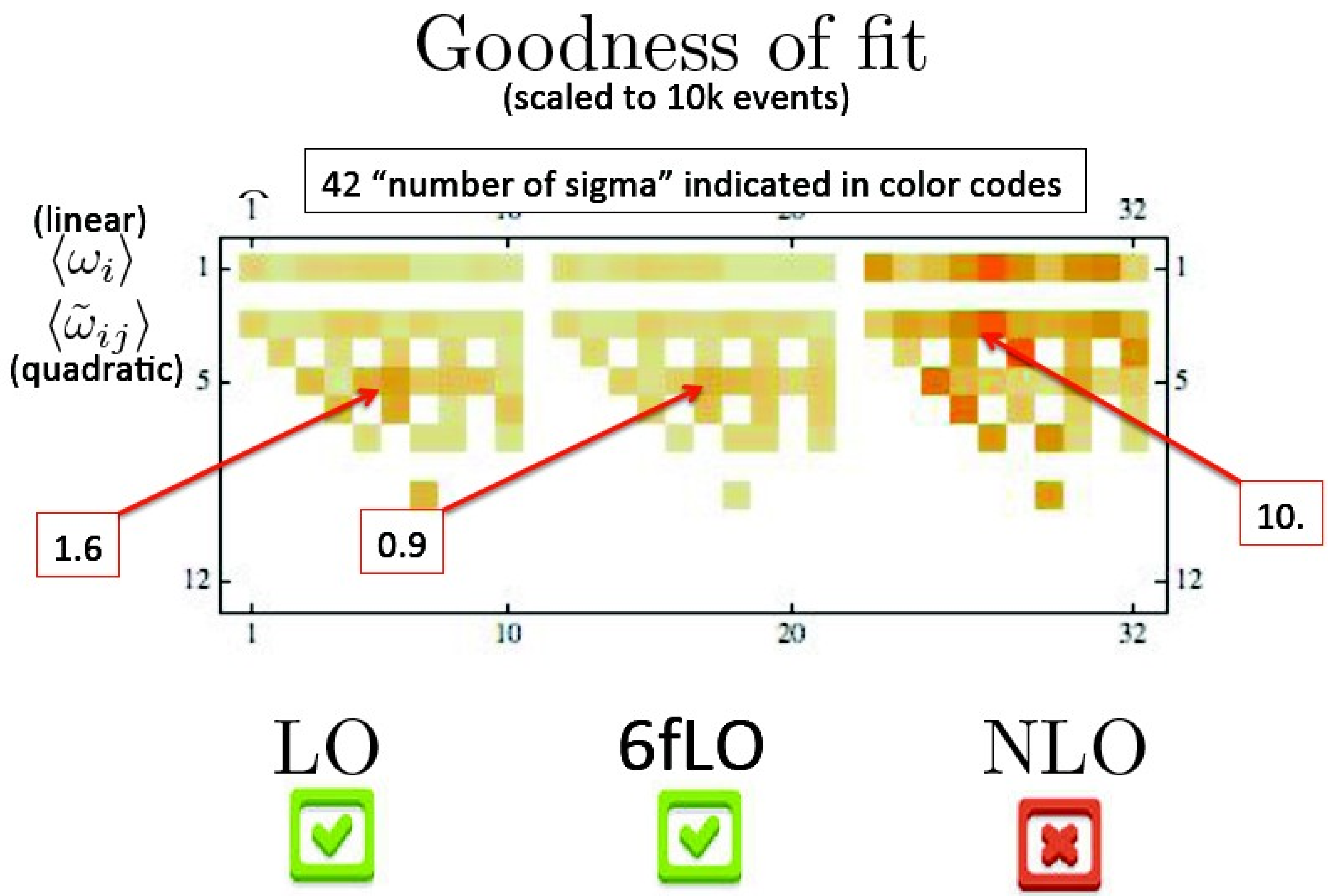
Show feasibility of kinematic reconstruction of the di-lepton final state: $e^+e^- \to t\bar{t} \to l^+\nu l^-\bar{\nu}b\bar{b}$

Optimal analysis extracts all ten form factors – simultaneously – from angular distribution using the (LO) matrix element

$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{1V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{1V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{1A}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{1A}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2V}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2A}$	$\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{Z}_{2A}$
0.0037	−0.18	−0.09	+0.14	+0.62	−0.15	0	0	0	0
	0.0063	+.14	−0.06	−0.13	+0.61	0	0	0	0
		0.0053	−0.15	−0.05	+0.09	0	0	0	0
			0.0083	+0.06	−0.04	0	0	0	0
				0.0105	−0.19	0	0	0	0
					0.0169	0	0	0	0
						0.0068	−0.15	0	0
							0.0118	0	0
								0.0069	−0.17
									0.0100

Sub-% precision. Note 0 correlation F2A with CP-conserving form factors
Lepton+jets final state, with same optimal ME extraction, yields factor two better precision

LO Matrix Element



Fitting a LO template to (all-order) data expected to lead to tension in the fit and bias of the parameters
Check fitting LO template to NLO-EW Monte Carlo → large χ^2 indeed reveals a problem
Work ongoing to extend analysis to NLO

Comparison to FCC-ee

P. Janot, arXiv:1503.01325, arXiv:1510.09056 assesses potential of FCC-ee

- run right above threshold; study assumes 2.4 ab^{-1} at $\sqrt{s}$ = 365 GeV

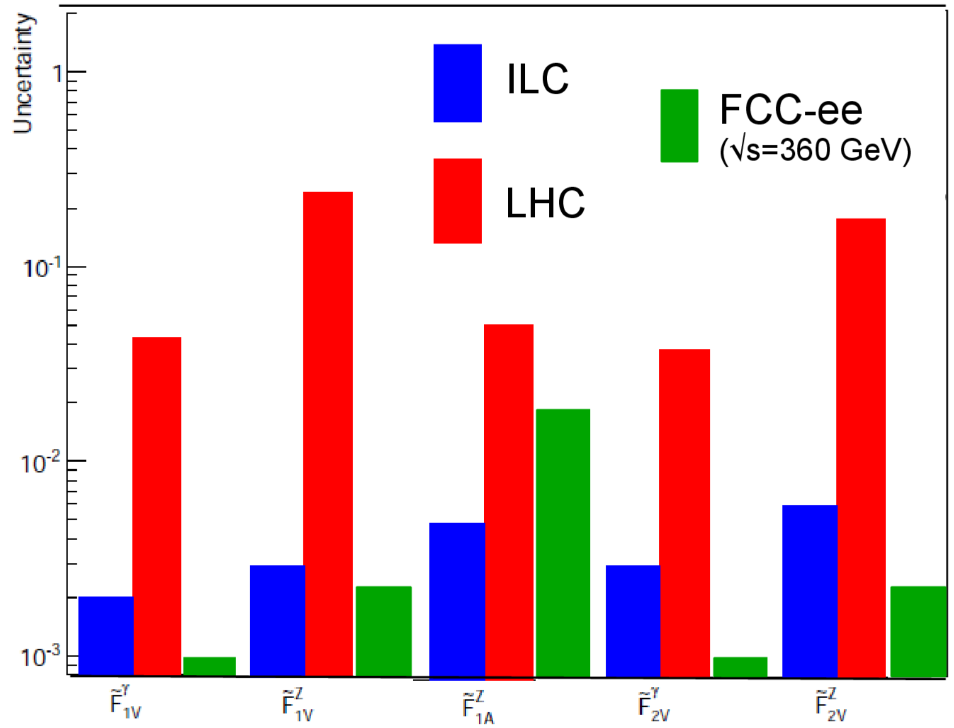
  (theory systematics close to threshold to be evaluated)

- no beam polarization, use final-state polarization instead

  (ILC beam polarization expected to be known to 10^{-3}, can one understand final state polarization to that level?)

Fast simulation analysis based on lepton energy and angle yields:

- similar precision to ILC for Z couplings, except F1AZ
- significantly better than ILC for photon couplings

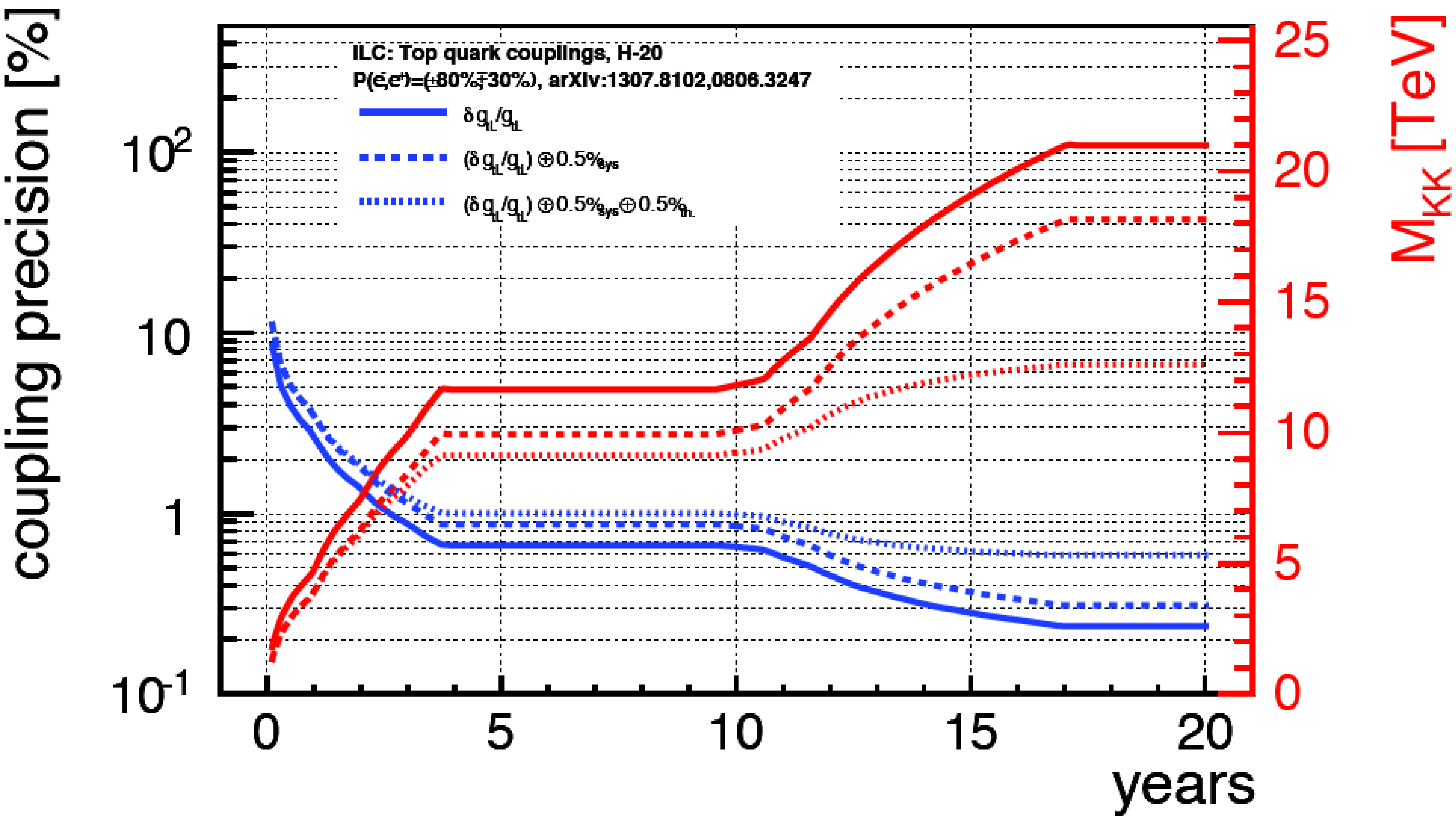


Good to see interest in this measurement

Full study needed to understand systematics

Complete 20-year ILC programme

H20: 500/fb @ 500 GeV, 200/fb @ 350 GeV, 500/fb @ 250 GeV, 3500/fb @ 500 GeV, 1500/fb @ 250 GeV



Sensitivity to new physics well beyond the direct kinematic reach
Systematics may limit potential in the long run → detailed study

CP violating couplings

The “baseline” study was limited to CP-conserving form factors, but e^+e^- is known to do well also for CP-violationg F2A at least since TESLA times

Reconstructing Bernreuther's optimal CP observables that measure differences in polarization orthogonal to production plane and in top quark flight direction.
In the lepton + jets final state:

$$O_+^{Re} = (\hat{q}_+^* \times \hat{q}_{\bar{X}}) \cdot \hat{e}_+ \qquad O_-^{Re} = (\hat{q}_-^* \times \hat{q}_X) \cdot \hat{e}_+$$

$$O_+^{Im} = -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{q}_X \cdot \hat{e}_+)^2]\hat{q}_+^* \cdot \hat{q}_X + \frac{\sqrt{s}}{2m_t}\hat{q}_X \cdot \hat{e}_+ \hat{q}_+^* \cdot \hat{e}_+$$

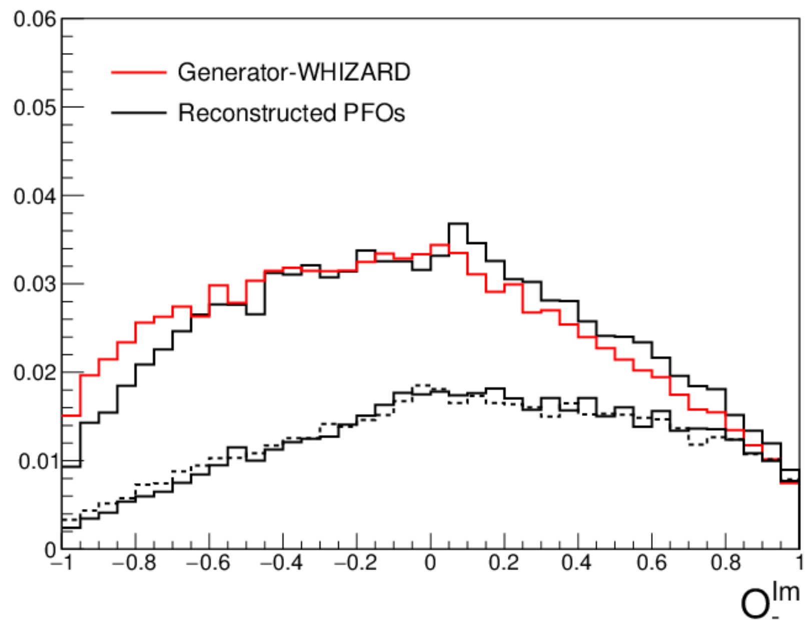
Where q= charged lepton momentum, X = hadronic top system, e = positron momentum

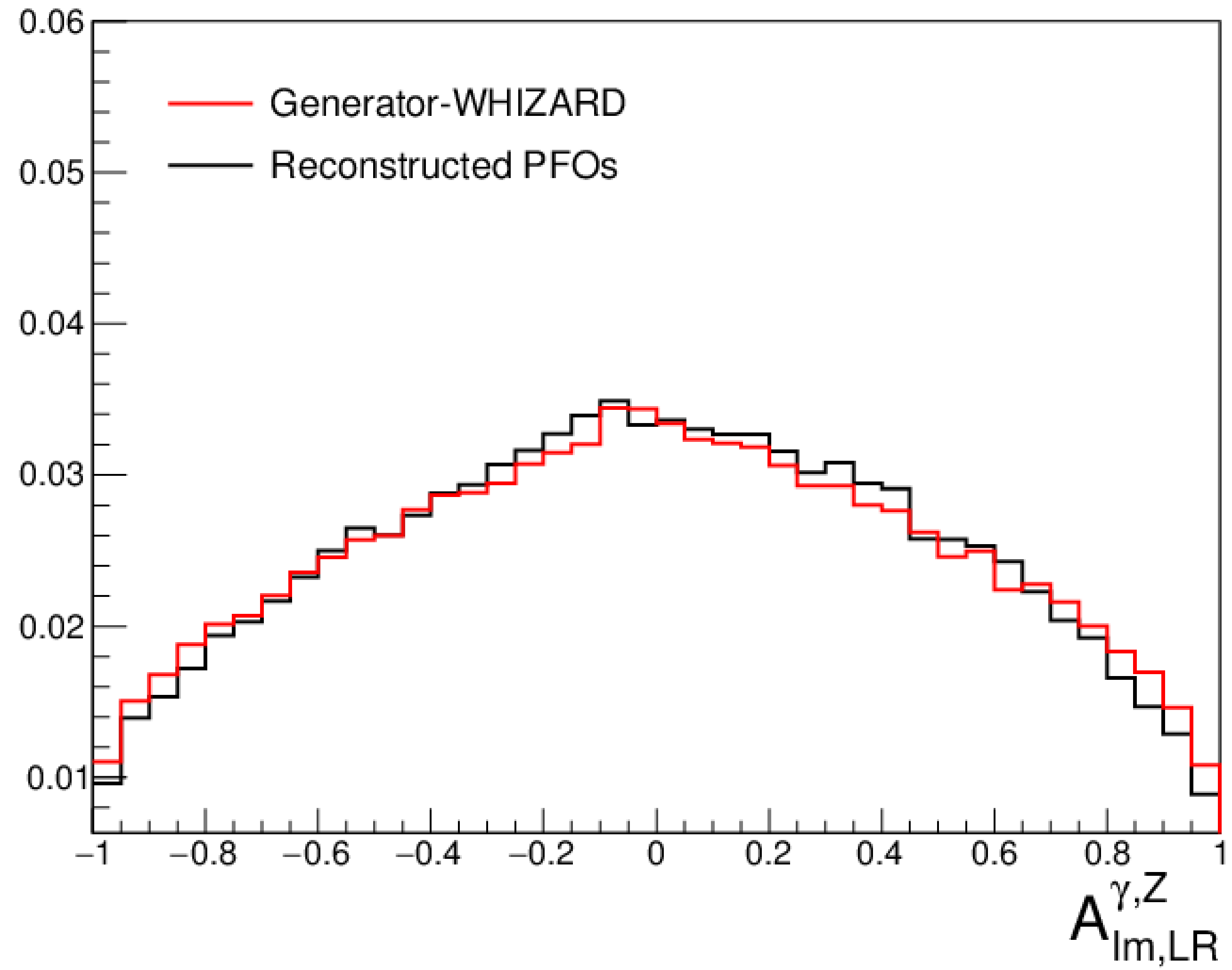
These observables have simple relations to the four F2A form factors:

$$A_{\gamma,Z}^{Re} = \langle O_+^{Re} \rangle - \langle O_-^{Re} \rangle = c_\gamma [P Re(F_{2A}^\gamma) + KZ Re(F_{2A}^Z)]$$

$$A_{\gamma,Z}^{Im} = \langle O_+^{Im} \rangle - \langle O_-^{Im} \rangle = d_\gamma [Im(F_{2A}^\gamma) + PKZ Im(F_{2A}^Z)]$$

F2A form factors





Significant migrations in the Oim distributions, largely cancel in asymmetry

Full simulation results exist for 500 GeV and 380 GeV.

Systematic uncertainties seem manageable.

Paper with updated numbers for LC potential in preparation

Top quark couplings: CPV Preliminary results

These observables have simple relations to the four F_{2A} form factors

$$A^{Re}_{\gamma,Z} = \langle O^{Re}_{+}\rangle - \langle O^{Re}_{-}\rangle = c_{\gamma}[PRe(F^{\gamma}_{2A}) + KZRe(F^{Z}_{2A})]$$

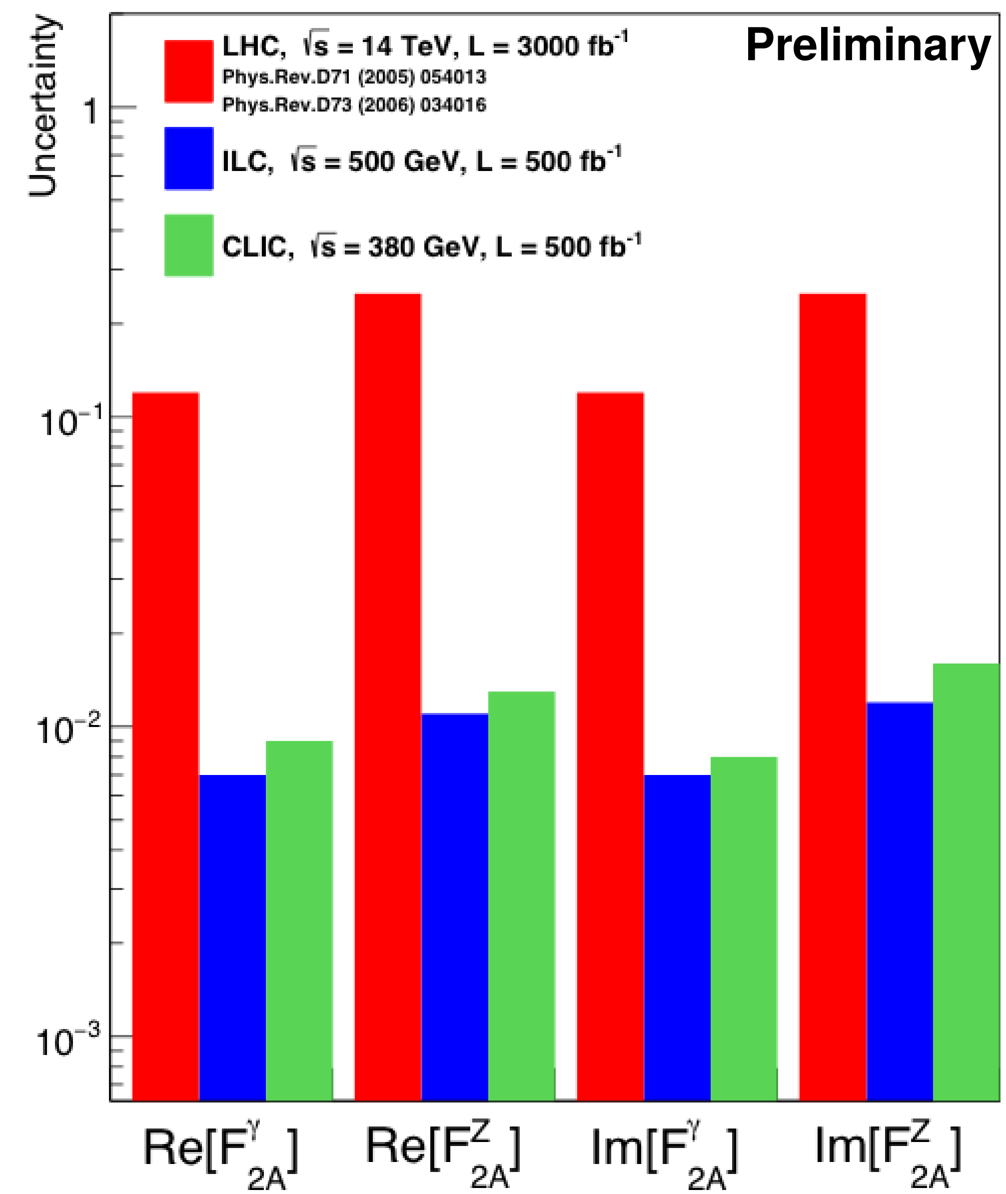
$$A^{Im}_{\gamma,Z} = \langle O^{Im}_{+}\rangle - \langle O^{Im}_{-}\rangle = d_{\gamma}[Im(F^{\gamma}_{2A}) + PKZIm(F^{Z}_{2A})]$$

One can easily isolate F_{2A} from previous lineal relations

Full simulations results exist for **ILC@500GeV** and **CLIC@380GeV**

Paper of LC potential in the CPV sector in preparation (IFIC-LAL collaboration)

Quantity	$Re[F^{\gamma}_{2A}]$	$Re[F^{Z}_{2A}]$	$Im[F^{\gamma}_{2A}]$	$Im[F^{Z}_{2A}]$
SM value at tree level	0	0	0	0
LHC	0.12	0.25	0.12	0.25
TESLA TDR	0.007	0.008	0.008	0.010
ILC@500 GeV	0.007	0.011	0.007	0.012
CLIC@380 GeV	0.009	0.013	0.008	0.016



Confirm sensitivity of TESLA TDR study

Lepton Collider top workshops

Series of workshops devoted to lepton collider top physics:

Paris (LAL) 2012 http://events.lal.in2p3.fr/conferences/Top-Quark-Physics/index.html
Paris (LPNHE) 2014 https://agenda.linearcollider.org/event/6296/
Valencia 2015 http://ific.uv.es/~toplc15/index.html

KEK, Tsukuba 2016 formal invitation to go out soon
keep 6-8 July free in your agenda
contact committee (Keisuke Fujii) for contributions

Top at lepton colliders: summary

Lepton Colliders have great top physics potential. Today's list, that only scratches the surface:

- Direct access to top quark Yukawa coupling, 4% precision ($\sqrt{s}$ > 550 GeV)

- Rare FCNC decays, BR (t → cH) ~ 10^{-5} ($\sqrt{s}$ ~ 500 GeV or 380 GeV)

- The ultimate top quark mass measurement, 50 MeV ($\sqrt{s}$ ~ 340-350 GeV)

- Exquisite BSM sensitivity through a characterization of $t\bar{t}Z/\gamma$ vertices

  sub-% precision on CP-conserving couplings ($\sqrt{s}$ ~ 500 GeV, some degradation at 380 GeV)

  Sub-% precision on CP-violation ($\sqrt{s}$ ~ 500 GeV/380 GeV)

Specifically for circular colliders:

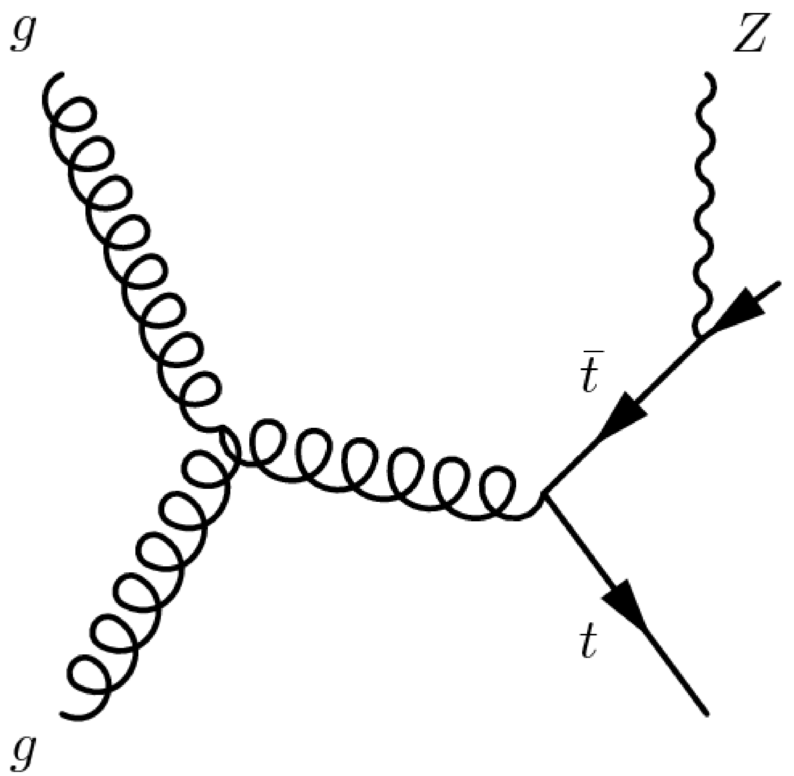
- *Expect 50 MeV precision on the top quark mass*
- *For couplings to Z/γ expectations similar to CLIC@380 GeV*
- *For Yukawa coupling, threshold scan allows O(20%) measurement*

Do not compare “targets” (i.e. stat. only) to “prospects” (based on best estimate of all uncertainties)

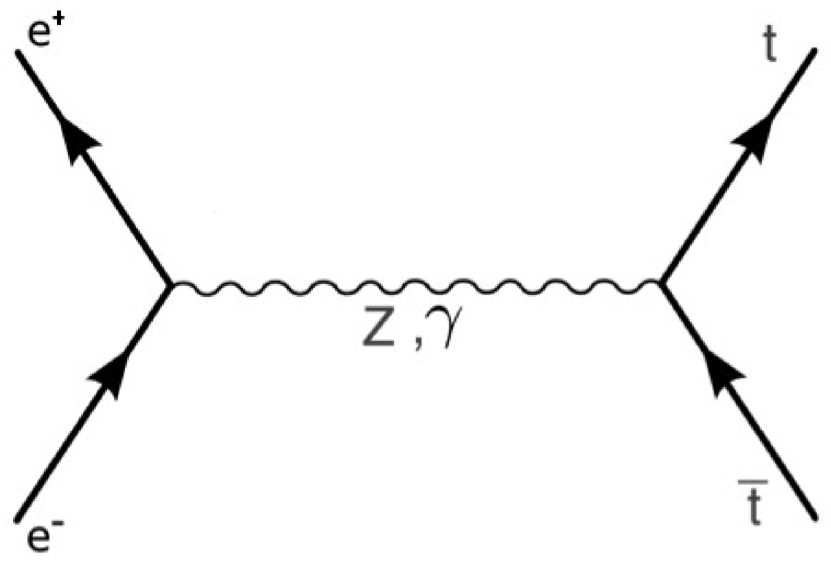
Top and Z/γ

Couplings of the top quark to neutral EW gauge bosons

At the LHC, $q\bar{q} \rightarrow Z/g \rightarrow t\bar{t}$ is inaccessible. Must use associated production



At a LC $e^+e^- \rightarrow t\bar{t}$ production is one of the most prominent 6f processes and readily isolated



Some overlap with studies of tWb vertex at LHC (single top, top decay), and indirect sensitivity of LEP precision tests and B-factories

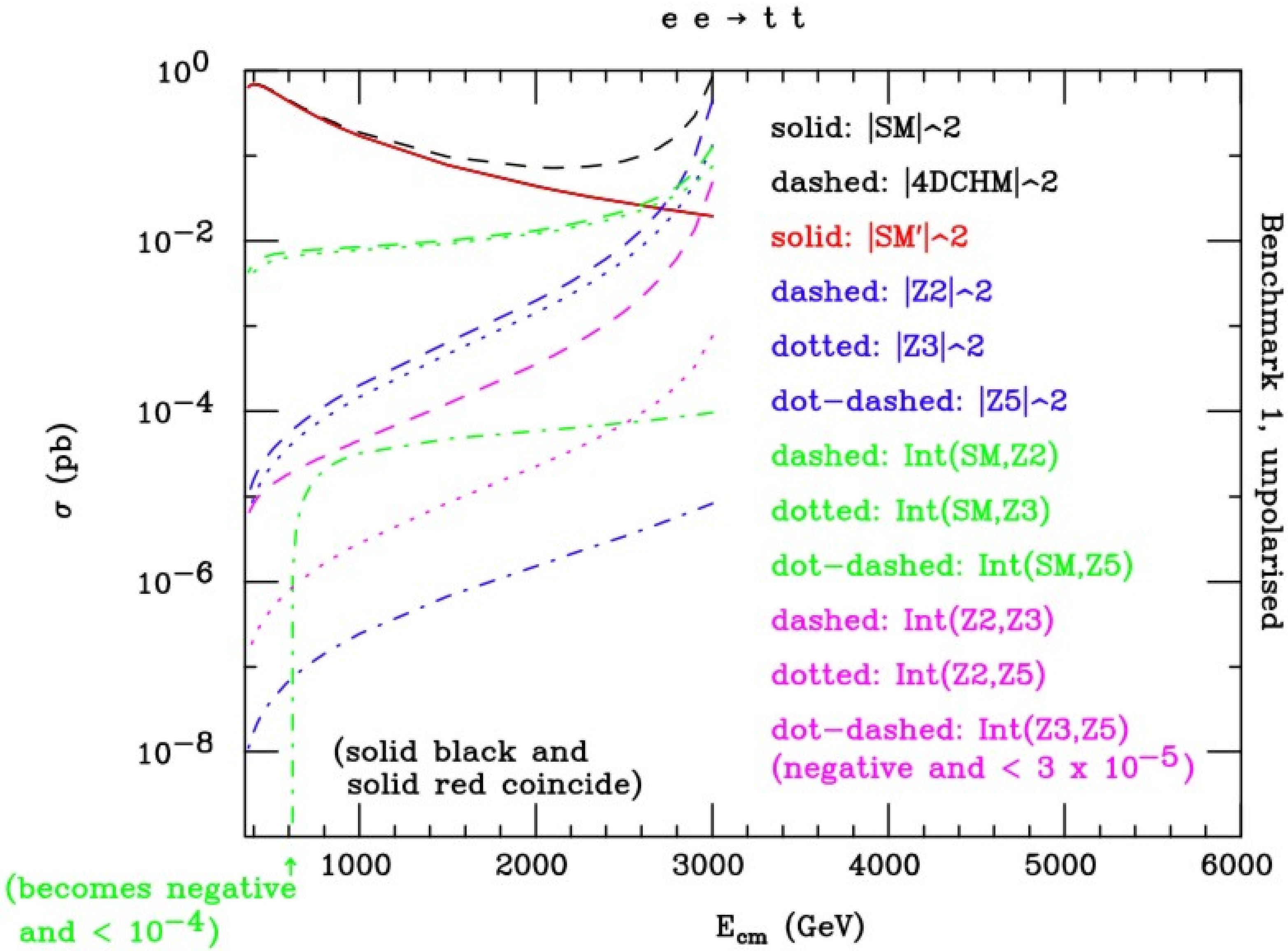
BSM physics: concrete model

A concrete example: the 4D Composite Higgs Model predicts for a benchmark point with mZ' ~ 3.1-4.3 TeV

$\Delta\sigma$ = 4% @380 GeV

= 9% @500 GeV

= 53% @1 TeV



4D Composite Higgs Model

Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

$$\frac{\delta y_t}{y_t} \sim \frac{(100+9) \times \frac{1}{2} \times \frac{\delta\sigma}{\sigma}}{9}$$

The expected statistical errors on top quark Yukawa coupling are 5.0% and 7.1% for the "Left" and "Right" polarization combinations, respectively, and 4.2% when combined (Table 3).

	"Left"	"Right"	Combined
cross section	0.84 %	1.2 %	
top quark Yukawa coupling	5.0 %	7.1 %	4.2 %